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TECHNICAL REPORT NO. 83-9

DEVELOPMENT OF THE MODEL 52500 STRAIN-INERTIAL SEISMOMETER SYSTEM (PROTOTYPE)

Sponsored by
Defense Advanced Research Projects Agency (DOD)
ARPA Order No. 2897 and 3328



ACKNOWLEDGMENT

This research was supported by the Advanced Research Projects Agency of the Department of Defense and was monitored by AFTAC/TGX, Patrick AFB, FL 32925, under Contract No. F08606-80-C-0014.

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TELEDYNE
GEOTECH

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TELEDYNE GEOTECH
3401 Shiloh Road
Garland, Texas 75041

15 May 1984

IDENTIFICATION

AFTAC Project No.: VT/0703
ARPA Order No.: 2897 and 3328
Project Title: Seismic Instrumentation
Contractor: Teledyne Geotech
Contract No.: F08606-80-C-0014
Effective Date: 15 April 1980
Expiration Date: 30 September 1983
Program Manager: R. D. Wolfe
214-271-2561
Garland, Texas 75041

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DTIC TAB <input type="checkbox"/>
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By _____
Distribution/ _____
Availability Codes
Approved for _____ or _____
Dist _____

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SUMMARY

Two prototype strain-inertial seismometer systems were designed and built to investigate the use of linear combinations of collocated strain and inertial data for providing enhanced seismic signal-to-noise ratios. These instruments have undergone initial laboratory testing and preliminary field evaluation.

The preliminary evaluation data indicate:

- ~(1) An improved signal-to-noise ratio can be achieved by using linear combinations of the strain and inertial data, the major improvement occurring in the frequency range of the cultural microseisms (3 to 5 Hz).)
- ~(2) A reduction in the instrument noise level of the strain output of the seismometer will be required prior to final evaluation.

1. INTRODUCTION

This technical report describes a prototype strain-inertial seismometer system which was designed, fabricated, and tested in the period 15 April 1980 to 31 August 1983. This report is submitted in compliance with Sequence Number 014/A2 of Contract Data Requirement List, Contract F08606-80-C-0014.

2. PURPOSE OF THE STRAIN-INERTIAL SYSTEM

Interest in the strain-inertial concept began in 1964 when Dr. Carl Romney presented theoretical arguments to demonstrate that linear combinations of appropriately filtered and normalized strain and inertial data could result in substantial signal-to-noise improvements in the detection of P waves when the earth noise consisted principally of single-mode Rayleigh waves.

In the ensuing years, a number of attempts were made to employ the strain-inertial concept. Major efforts in the application of strain seismographs were reported by Shopland and Kirkland (1970) and by Fix and Sherwin (1972). These and other attempts produced only limited results, and investigations in this area were terminated in the early 1970's.

In retrospect, the unsatisfactory performance of these early systems may be attributed to a number of factors, as follows:

1. Electronic Noise - The electronic noise level of the best available amplification devices was excessive when compared with the extremely small signals developed by the strain transducers.
2. Spatial Decorrelation - Decorrelation of earth noise and signal fields over distances of even a few meters had not been recognized during the investigations with the early strain systems (cf. Mrazek et al, 1979).
3. Environmental Noise - Induced noise at the earth's surface due to wind, atmospheric pressure fluctuations, and temperature changes often masked the actual strain motion (cf. Douze, 1964).

During 1979, as a result of an improved understanding of the problems which had limited the early strain investigations, a renewed interest in the strain-inertial concept developed, culminating in a study by Sorrells and Starkey (1980) on the current possibilities of utilizing strain-inertial data for signal-to-noise enhancement.

A new design concept for a strain-inertial seismometer system was put forward which addressed the early system limitations, as follows:

1. Electronic Noise - Ultra low noise amplifying devices had been developed as a part of the technology for the KS 36000 seismometer which would overcome the electronic noise problems in the early systems.
2. Spatial Decorrelation - The new design concept for the strain-inertial seismometer would sense inertial motion and strain motion at a single point with a very short strain interval (1 meter).
3. The new strain-inertial seismometer would be installed in a sealed, insulated borehole at a depth of 40 meters to eliminate interference from environmental noises at the earth's surface.

In April 1980, a project was initiated to design, fabricate, and test two strain-inertial seismograph systems embodying the new concepts. This research was sponsored by the Advanced Research Projects Agency of the Department of Defense and accomplished under the technical direction of the Air Force Technical Applications Center.

REFERENCES

- Douze, E. J., 1964, Noise attenuation in shallow holes, Teledyne Geotech, Technical Report 64-135, 29 p.
- Fix, James E., and John R. Sherwin, 1972, Development of LP wave discrimination capability using LP strain instruments, Technical Report 72-3, Teledyne Geotech, 537 p., 6 app.
- Mrazek, C. P., Z. A. Der, B. W. Barker and A. O'Donnell, 1979, Mode of propagation and coherence structure of the regional phases P_n , P and L_g and optimum array configurations for their enhancement, paper delivered at DARPA Program Review - Regional Seismic Detection and Discrimination.
- Romney, Carl, 1964, Combinations of strain and pendulum seismographs for increasing the detectability of P: Bull. Seism. Soc. Am., v. 54, no. 6B, p. 2165-2174.
- Shopland, Robert C., and Richard H. Kirklin, 1970, Application of a vertical strain seismograph to the enhancement of P waves: Bull. Seism. Soc. Am., v. 60, p. 105-124.
- Sorrells, G. G., and O. D. Starkey, 1980, An assessment of the use of strain and inertial seismographs to enhance seismic signal-to-noise ratio, 7 March 1980, Technical Report No. 80-6: Garland, Texas, Teledyne Geotech, 54 p., 1 app.

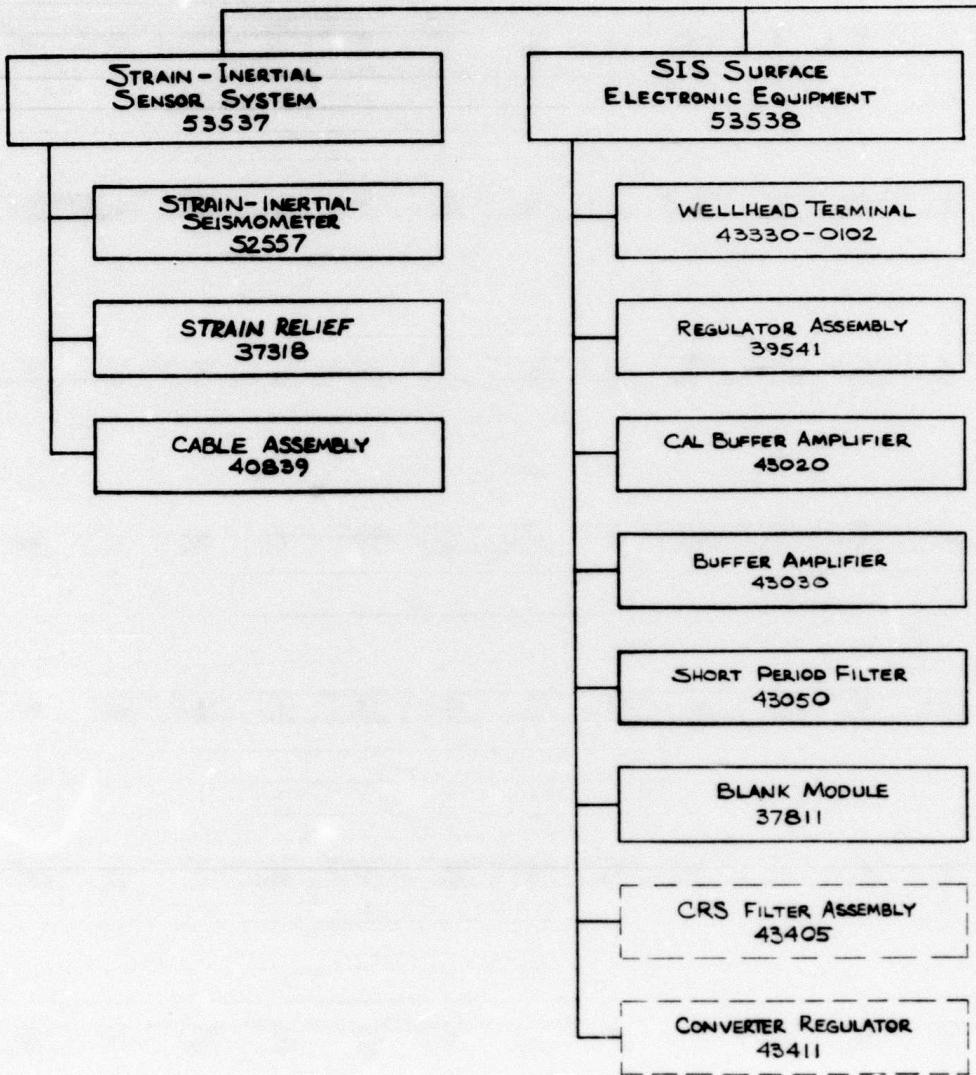
3. DESCRIPTION OF THE SYSTEM

3.1 GENERAL

The strain-inertial seismometer system consists of the following equipment groups:

1. Strain-Inertial Sensor System - A borehole seismometer designed to sense both inertial and strain motion together with its associated downhole accessories.
2. SIS Surface Electronic Equipment - A wellhead terminal unit designed to condition the electrical power and calibration signals required by the seismometer and to provide initial analog processing of the strain and inertial signals generated by the seismometer.
3. Strain-Inertial Borehole - A cased borehole designed to provide instrument bearing seats at a depth of 40 meters and an internal environment free from atmospheric disturbances.
4. Installation and Handling Equipment - The accessory equipment required to place the strain-inertial system in operation.
5. Winch and Mast - These equipment items are defined by the system but are not considered integral components.

A breakdown is provided in figure 1 to illustrate the organization of the overall strain-inertial system. A photograph of the strain-inertial seismometer with its outer cases and floating stabilizer removed is shown in figure 2, and a photograph of the wellhead terminal is given in figure 3.



NOTE: EQUIPMENT UNITS SHOWN IN SOLID BOXES
ARE FOR 52500-0101; EQUIPMENT UNITS
SHOWN IN DASHED BOXES ARE FOR OTHER VERSIONS.

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(1)

STRAIN - INERTIAL
SEISMOMETER SYSTEM
MODEL 52500

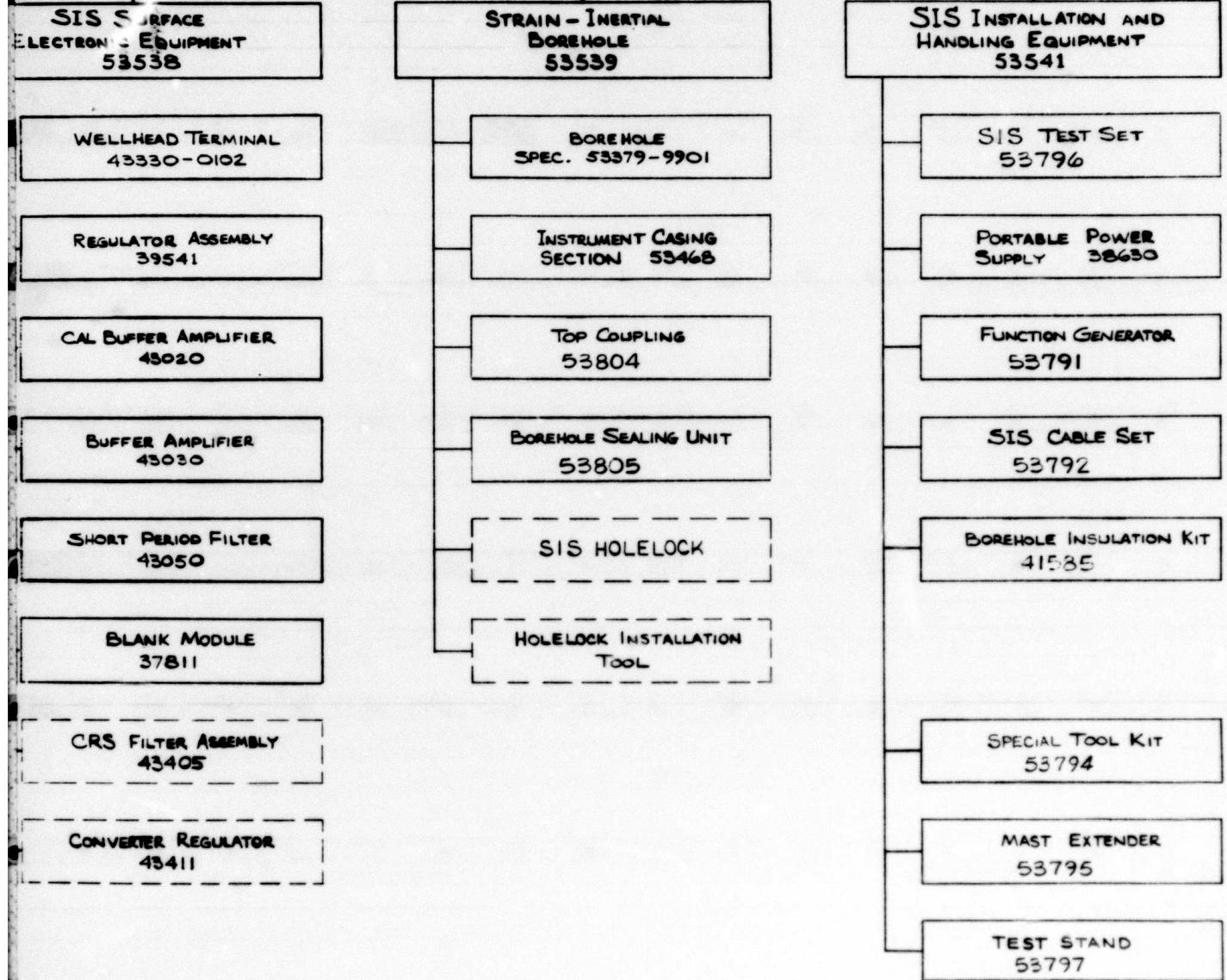


FIGURE 1

(2)

EM

DI

NG
68

UNIT

K

LATION

SIS INSTALLATION AND
HANDLING EQUIPMENT
53541

EQUIPMENT REQUIRED
BUT NOT SUPPLIED

SIS TEST SET
53796

WINCH
38760

PORTABLE POWER
SUPPLY 38630

MAST
43296

FUNCTION GENERATOR
53791

SIS CABLE SET
53792

BOREHOLE INSULATION KIT
41585

SPECIAL TOOL KIT
53794

MAST EXTENDER
53795

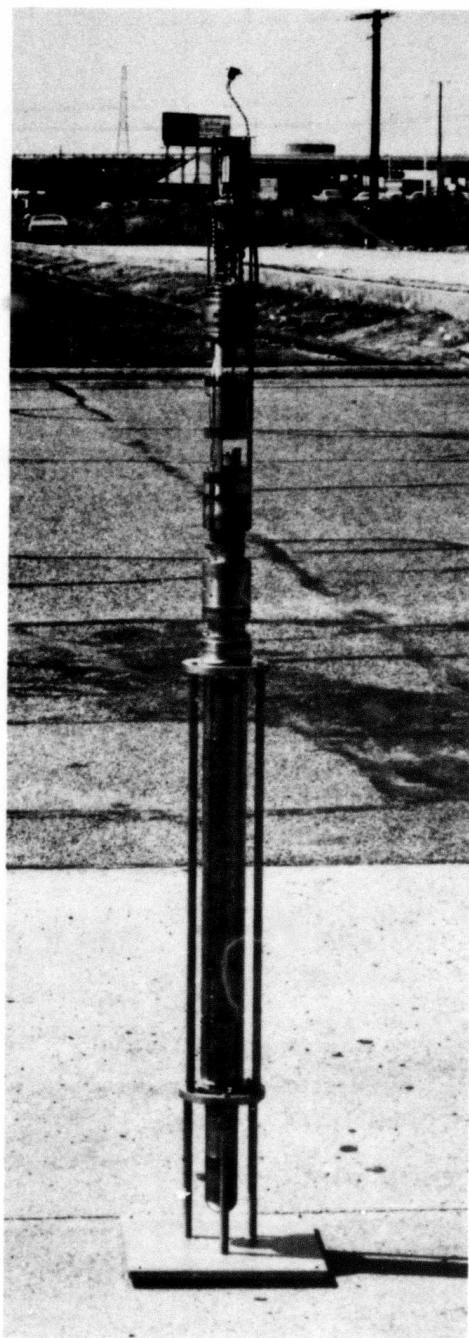
TEST STAND
53797

FIGURE 1. BREAKDOWN ORGANIZATION FOR THE
STRAIN-INERTIAL SEISMOMETER SYSTEM

G 14476

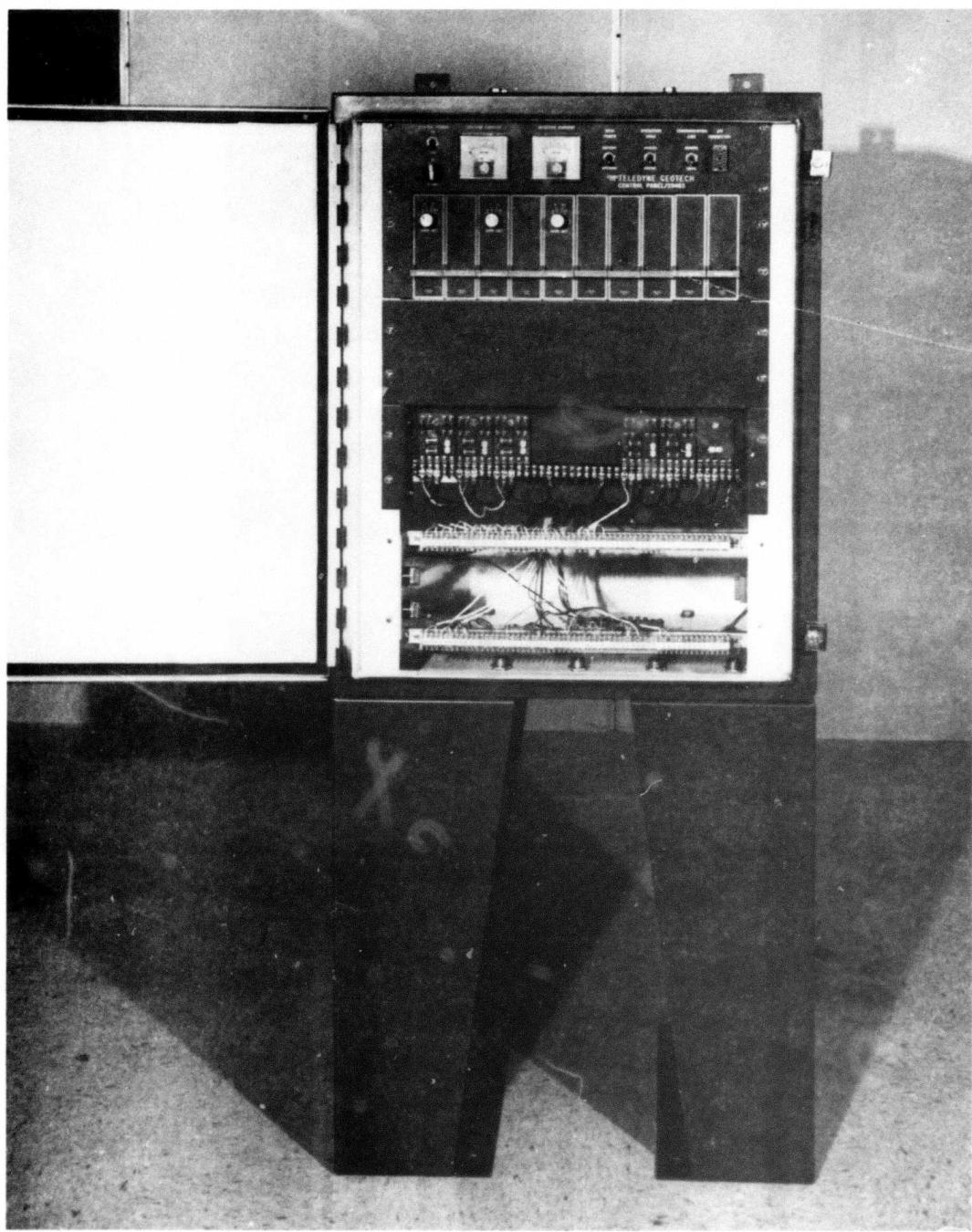
3-3/4

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P21067

FIGURE 2. STRAIN INERTIAL SEISMOMETER WITH OUTER CASES REMOVED



P19718

FIGURE 3. SIS WELLHEAD TERMINAL

3.2 STRAIN-INERTIAL SENSOR SYSTEM

The strain-inertial sensor system is the designation applied to the downhole elements of the strain-inertial system. These elements are:

- 1. The strain-inertial seismometer.**
- 2. The armored signal cable.**
- 3. The cable strain relief.**

The strain-inertial seismometer incorporates a lower seating cone, an upper seating cone and a floating stabilizer. Earth strain is measured between the lower and upper seating cones, which are one meter apart. Inertial motion is measured from the upper seating cone. The floating stabilizer allows the top of the seismometer to take up a position as dictated by the two cones as they make contact with the instrument seats in the borehole. As tension is released on the seismometer cable, the stabilizer locks the top of the seismometer in place.

The armored seismometer cable provides twelve insulated conductors to connect the seismometer and the surface electronics. The armor serves as strength member, shield and ground conductor.

The cable strain relief locks in place in the borehole as tension on the seismometer cable is released. This device prevents mechanical forces in the armored cable from coupling to the seismometer, during operation.

3.3 SIS SURFACE ELECTRONIC EQUIPMENT

The surface electronic equipment for the strain-inertial system consists of a wellhead terminal and a group of modules to provide downhole power and processed calibration signals to the seismometer and to provide initial processing for the seismometer output signals. A photograph of the surface electronic equipment is shown in figure 3.

3.4 STRAIN-INERTIAL BOREHOLE

The strain-inertial borehole was specifically designed for the strain-inertial seismometer and consists of the following three major elements:

- 1. Thirty-six meters of standard steel casing with an outer diameter of 7 inches.**
- 2. A special bottom section with two instrument seats and a compliant interval to allow the earth strain to be transmitted to the instrument.**
- 3. A top sealing system to prevent atmospheric pressure changes from being transmitted into the interior of the borehole.**

The borehole casing string is cemented in place in accordance with an installation procedure included in the system drawing set. The effective installation depth of the borehole is 40 meters.

3.5 INSTALLATION AND HANDLING EQUIPMENT

This set of equipment includes the system-specific items required for pre-installation tests, handling, field installation, initial adjustment, and system calibration. A test stand is included to hold the strain-inertial seismometer in an operational position for surface testing. A mast extender, borehole insulation kit, and special tool kit are included for use in the installation procedure. A test set, function generator, portable power supply, and associated cables are provided for initial system calibration.

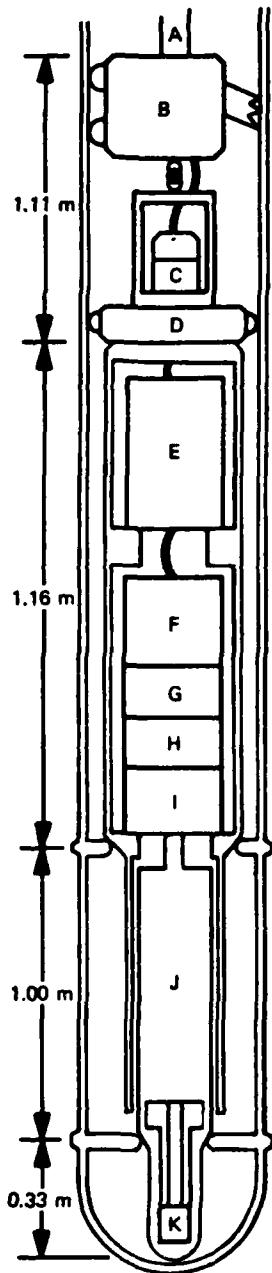
3.6 WINCH AND MAST

The strain-inertial system has been designed to utilize the cable winch and borehole mast that is used for the KS 36000 seismometer. Because the length of the strain-inertial seismometer is greater than that of the KS 36000 seismometer, a mast extender is required. This extender, furnished as a part of the SIS installation and handling equipment, can be removed.

4. DESCRIPTION OF STRAIN-INERTIAL SEISMOMETER

4.1 GENERAL

The strain-inertial seismometer is a sealed borehole instrument with a case diameter of 5 inches and an overall length of approximately 98 inches. The instrument contains a vertical strain seismometer, a vertical inertial seismometer, and circuits for amplification, calibration, and control. A schematic representation of the strain-inertial seismometer and associated equipment in an operating configuration in the borehole is given in figure 4. A breakdown showing the organization of the instrument is given in figure 5.



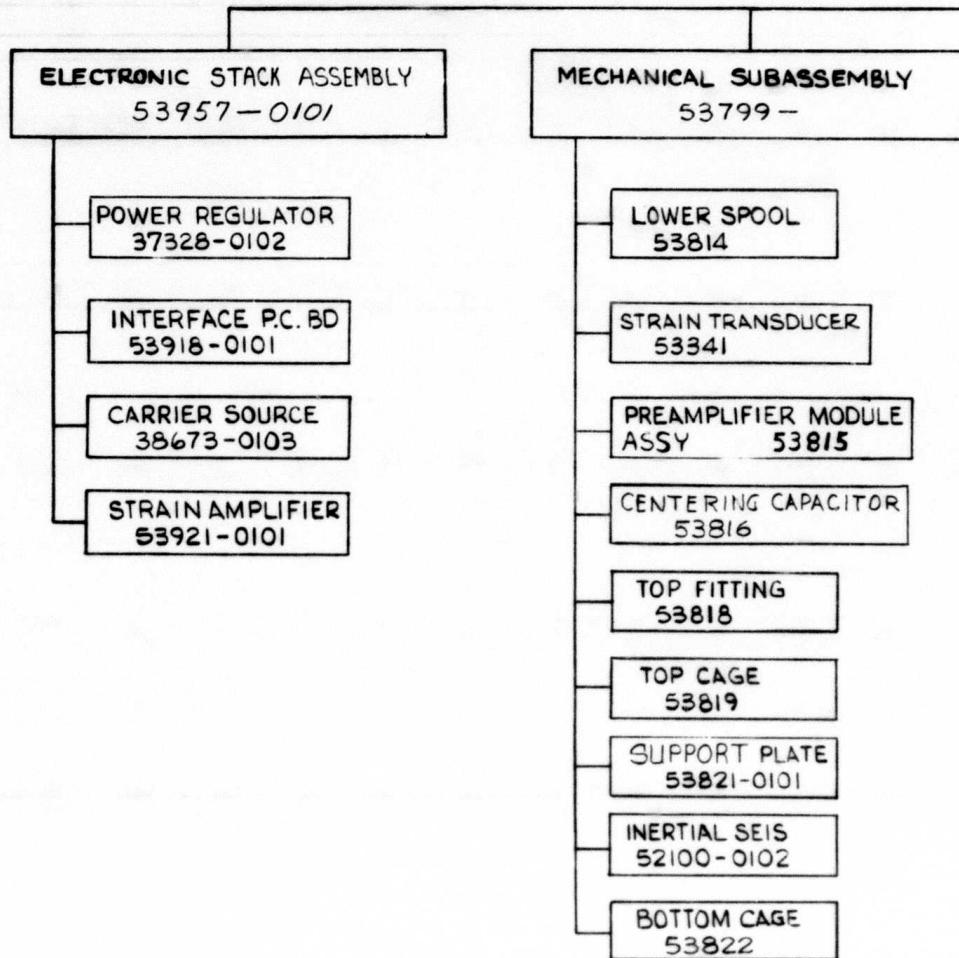
LEGEND

- A - ARMORED CABLE
- B - STRAIN RELIEF
- C - CABLE HEADER
- D - FLOATING STABILIZER
- E - SYSTEM ELECTRONICS
- F - INERTIAL MODULE
- G - CENTERING CAPACITOR
- H - PREAMPLIFIER MODULE
- I - STRAIN TRANSDUCER
- J - STRAIN ROD
- K - STRAIN CALIBRATOR

NOTE: OVERALL LENGTH = 3.60 m
CASE DIAMETER = 0.13 m

FIGURE 4. STRAIN-INTERIAL SEISMOMETER SCHEMATIC REPRESENTATION.

G 14474



4 3/4

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(1)

STRAIN-INERTIAL SEISMOMETER
52587

ICAL SUBASSEMBLY
 53799 -

OWER SPOOL
 53814

RAIN TRANSDUCER
 53341

EAMPLIFIER MODULE
 SY 53815

NTERING CAPACITOR
 53816

DP FITTING
 53818

DP CAGE
 53819

UPPORT PLATE
 53821-0101

ERTIAL SEIS
 5100-0102

OTTOM CAGE
 53822

- BASE CONE, 54017-0101
- STRAIN ROD, 54012-0101
- ROD COVER, 54011-0101
- COUPLING BASE, 54008-0101
- COUPLING ROD, 54007-0101
- COUPLING PLATE, 54009-0101
- CALIBRATOR CAP
54013-0101
- CALIBRATOR BODY
54014-0101
- CALIBRATOR ROD
54002-0101
- CALIBRATOR POLE PIECE
54001-0101
- CALIBRATOR COIL
54016-0101
- CALIBRATOR MAGNET
54004-0101
- GUIDE RING
54015-0101
- COUPLING RING
54673-0101
- COUPLING PIN
54595-0101

STRAIN ROD COMPONENTS

RING 38132-0101

STABILIZER UNIT
 53808

HEADER 38312-0101

HEADER PLATE 38185-0101

STABILIZER ACTUATOR
 53809

ANCHOR PLATE
 54594-0101

BAIL
 38144-0101

HEADER-STABILIZER COMPONENTS

FIGURE 5.

(2)

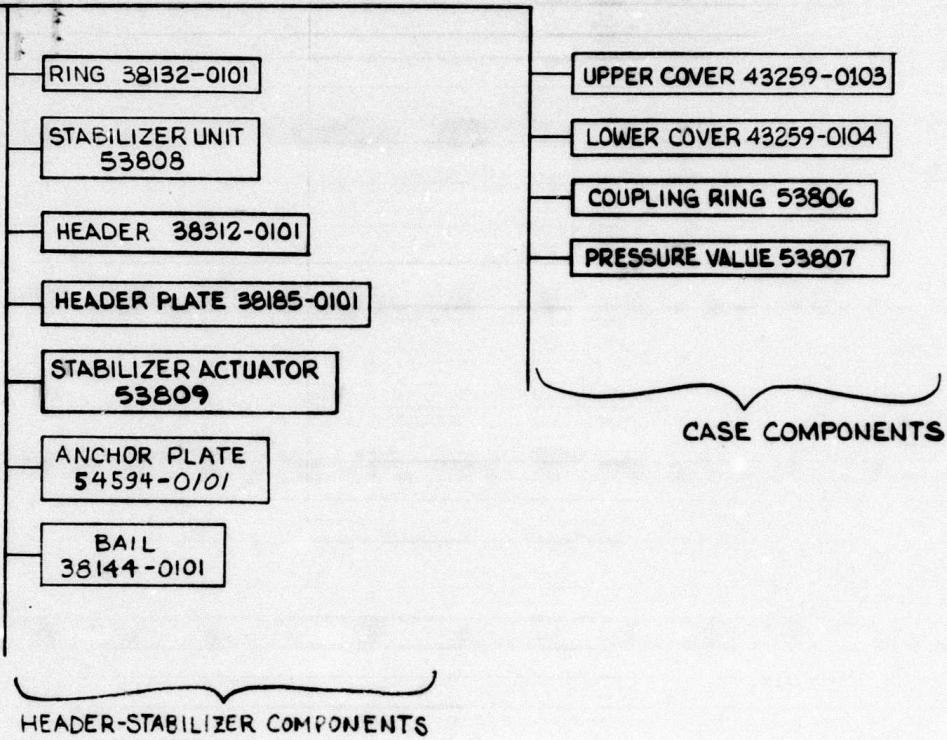


FIGURE 5. BREAKDOWN ORGANIZATION FOR STRAIN-INERTIAL SEISMOMETER

G 14475

4-3/4

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4.2 MECHANICAL SUBASSEMBLY

The mechanical subassembly of the strain-inertial seismometer (designated by items F, G, H, and I) is shown in figure 4. A photograph of the mechanical subassembly is given in figure 6 which presents a more detailed view. The elements shown in figure 6 are:

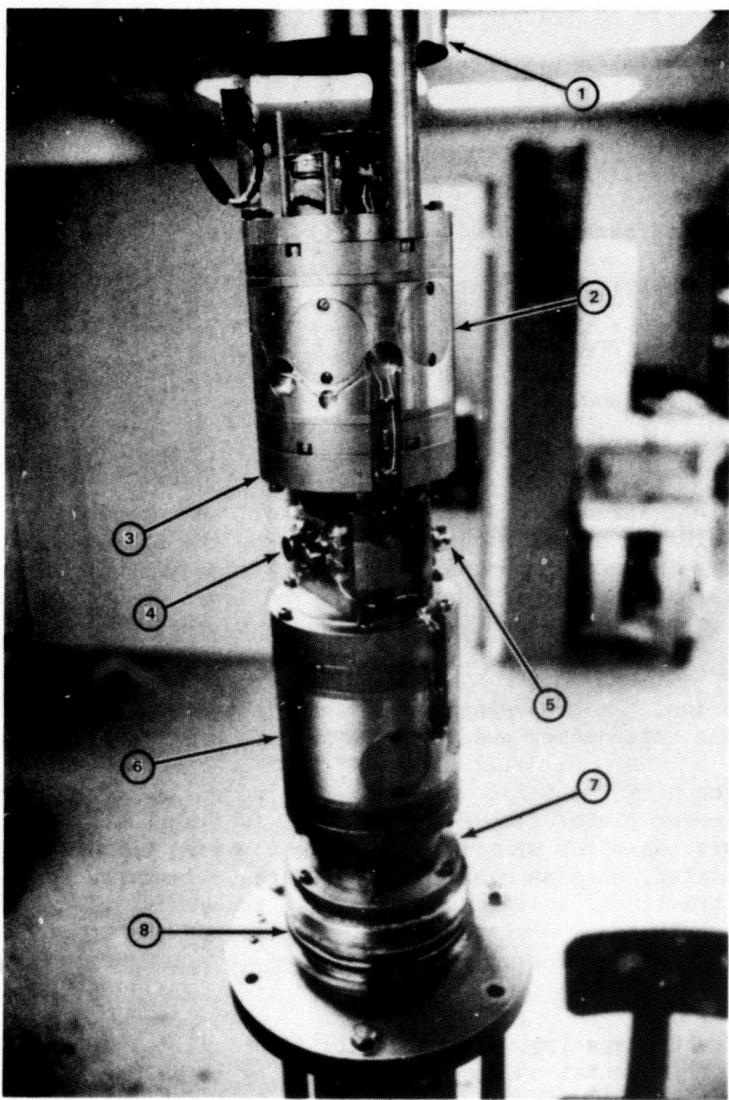
1. Inertial seismometer
2. Centering capacitor
3. Preamplifier module
4. Transformer printed circuit (PC) unit
5. Preamplifier PC unit
6. Strain transducer
7. Lower spool
8. Base cone (seis case element)

The strain transducer, centering capacitor, and preamplifier module (with its preamplifier PC and transformer PC) make up the strain detection bridge. The inertial seismometer mounts in the upper frame of the mechanical subassembly and contains a preamplifier PC unit. The lower spool is a mounting element used to attach the mechanical subassembly to the base cone of the seismometer case.

In summation, the mechanical subassembly contains the inertial seismometer, the strain seismometer and their respective preamplification circuits.

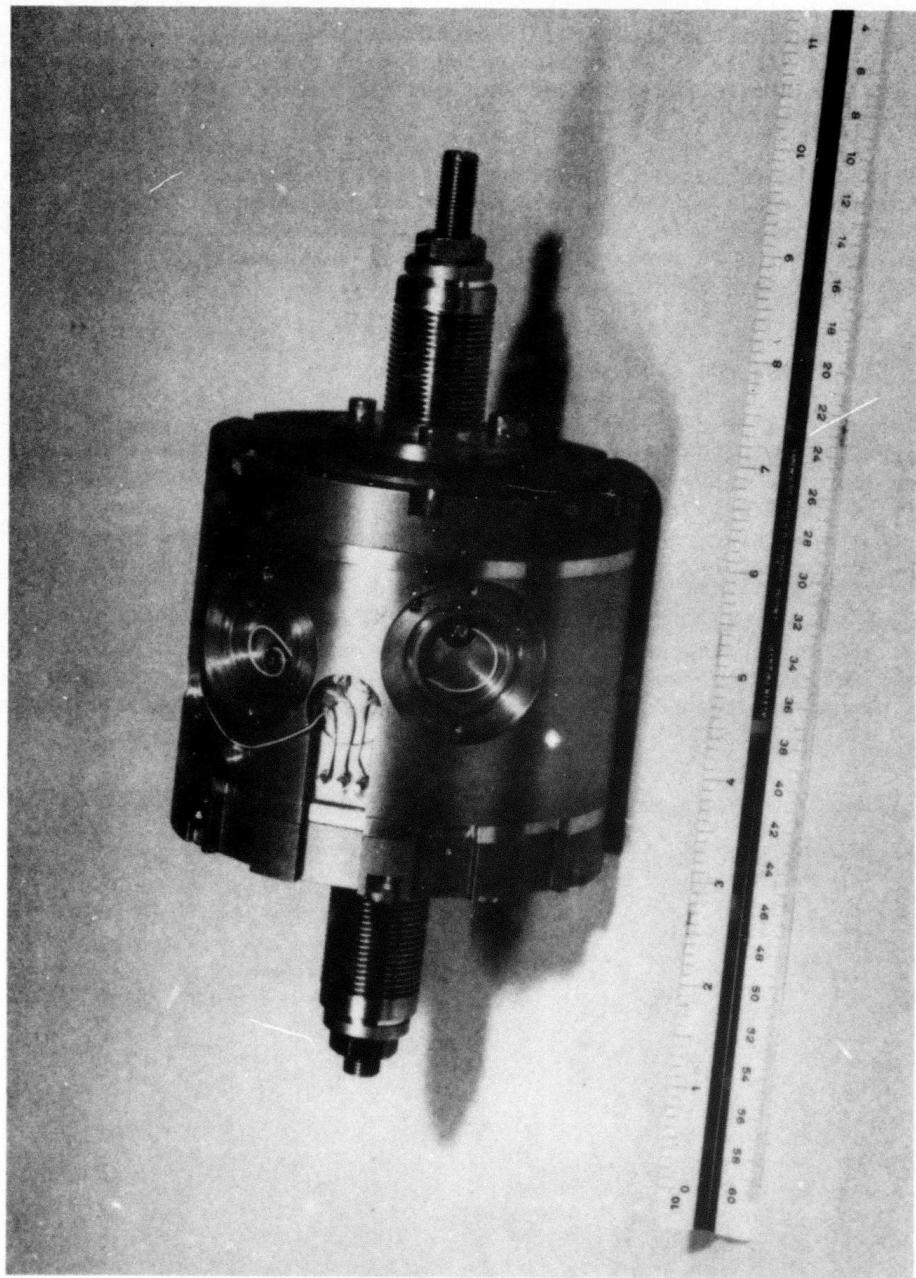
A photograph of the strain transducer is shown in figure 7 with the coupling rod and cover plates removed. This unit is a three-terminal device with two stationary capacitor plates and a central moving capacitor plate. The shape of the plates, plus an overlapping feature, allows the transducer to serve as an ultra-linear voltage divider. The transducer is driven through its central shaft by excursions at the upper end of the strain rod. Bellows at either end of the central shaft allow the interior of the transducer to be sealed.

The centering capacitor is internally identical to the strain transducer; however, the central shaft of the centering capacitor is driven by a motor unit and controlled from the surface electronics.



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FIGURE 6. PHOTOGRAPH OF STRAIN-INERTIAL MECHANICAL SUBASSEMBLY



P20425

FIGURE 7. PHOTOGRAPH OF STRAIN TRANSDUCER

4.3 ELECTRONIC STACK ASSEMBLY

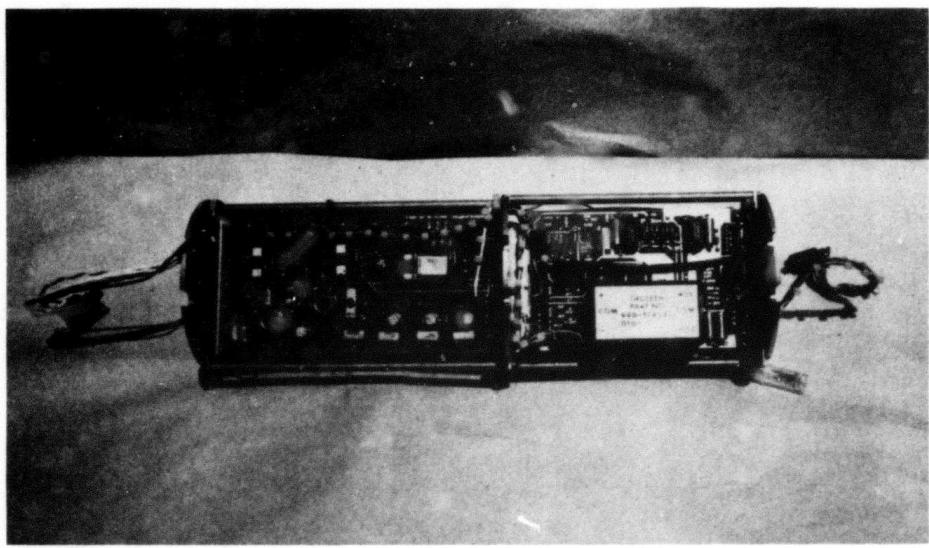
The electronic stack assembly consists of four PC units and a metal frame for mounting them within the seismometer. The position of the electronic subassembly within the strain-inertial seismometer is illustrated in the schematic representation in figure 4. A photograph of the electronic stack assembly showing the power regulator PC unit and the carrier source PC unit is given in figure 8. A second photograph of the electronic subassembly showing the strain amplifier PC unit and the interface PC unit is given in figure 9.

An electronic cable on the upper end of the subassembly connects through the seismometer cable to the surface electronic equipment. Two cables interconnect the electronic subassembly to the mechanical subassembly. The functions of the PC units of the mechanical subassembly will be described in section 5 of this report.

4.4 STRAIN ROD AND COUPLING

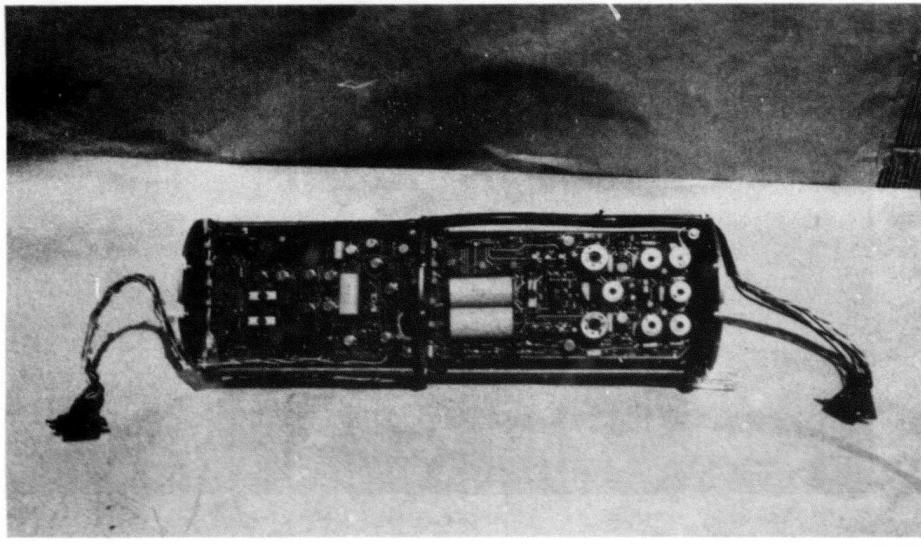
The strain rod is designated by item J in figure 4. It spans a one-meter interval between the upper and lower instrument seats of the strain-inertial borehole. The upper end of the strain rod connects to the movable central shaft of the strain transducer through a rigid coupling mechanism. The lower end of the strain rod is a conical base which rests on the lower instrument seat.

The strain-inertial borehole incorporates a compliant section between the upper and lower instrument seats, allowing earth strain to register accurately between the two instrument seats. The earth strain is then transferred into the strain transducer through the rigid strain rod and coupling mechanism.



M-211

FIGURE 8. PHOTOGRAPH OF ELECTRONIC STACK ASSEMBLY SHOWING THE POWER REGULATOR AND CARRIER SOURCE PC UNITS



M-210

FIGURE 9. PHOTOGRAPH OF ELECTRONIC STACK ASSEMBLY SHOWING THE STRAIN AMPLIFIER AND INTERFACING PC CIRCUITS

4.5 STRAIN CALIBRATOR

The strain calibrator mechanism is built into an extension of the strain rod below the lower conical base. The arrangement of the calibrator is shown as item K in the schematic representation in figure 4. A calibration coil mounted on the lower end of a calibration rod resides in a strong magnetic field produced by a magnetic assembly attached in the base cavity of the calibrator housing. When current is passed through the calibrator coil, a vertically oriented force is produced and transmitted upward through the calibration rod to act on a thin-wall section of the strain rod.

The length of the thin-wall section is changed in proportion to the calibration force, which in turn is proportional to the calibration current. The change in length of the thin-wall section of the strain rod is registered by the strain transducer as equivalent earth strain.

4.6 STABILIZER UNIT

The stabilizer unit is shown as item D in the schematic representation of the strain-inertial seismometer in figure 4. The stabilizer unit is a cylindrical ring with three captive steel balls positioned about its outer circumference. As long as tension is on the seismometer cable, the stabilizer floats freely about the seismometer header. As the seismometer comes to rest in the instrument seats of the borehole and the cable tension diminishes, a yoke mechanism presses the three balls outward to firmly contact the borehole casing and locks the stabilizer in position with respect to the seismometer.

This sequence of events brings about the following results:

1. The position of the seismometer in the borehole is established solely on the basis of the seating of the instrument in the upper and lower instruments seats of the borehole.
2. Once this position is established, it is stabilized as the action of the yoke mechanism locks the stabilizer unit in place.

4.7 SEISMOMETER CASE AND HEADER

The case of the strain-inertial seismometer is a sealed, 5-inch diameter cylinder extending from the sealed cable header to the base cone. A cylindrical extension of the case serves as a sheath for the strain rod. Sealing of the bottom portion of the seismometer occurs within the strain transducer and preamplifier module where a pressure equilization chamber exists. This system is employed so that any minor pressure variation occurring within the sealed borehole will be applied equally at both ends of the strain transducer, thus eliminating sensitivity to barometric signals.

The sealed case of the strain-inertial seismometer is equipped with a pressure fitting which allows the unit to be evacuated and backfilled with helium gas. This procedure provides a moisture-free environment for the electronics and also greatly attenuates any effects from thermal convections within the seismometer case.

5. STRAIN-INERTIAL SYSTEM CIRCUITRY

5.1 GENERAL

A block diagram of the strain-inertial system electronics is shown in figure 10. This diagram presents the system on a modular basis to allow convenient analysis of the various system functions. The system modules are arranged in two major groups: those contained in the borehole package of the strain-inertial seismometer and those contained in the wellhead terminal at the surface.

5.2 SYSTEM POWER AND GROUND

The strain-inertial system is powered from a single source (+22/28 volts) connected to the dc/dc converter in the wellhead terminal. The converter supplies +28 volts to two system regulators from terminals (TBI-13 and TBI-14) in the wellhead terminal. The power regulator in the wellhead terminal supplies +15 volts to all surface modules. The power regulator module in the strain-inertial seismometer supplies +15 volts and +6 volts to all downhole modules. Both of these power modules employ monolithic voltage regulators to provide stable, low-noise power sources for the system.

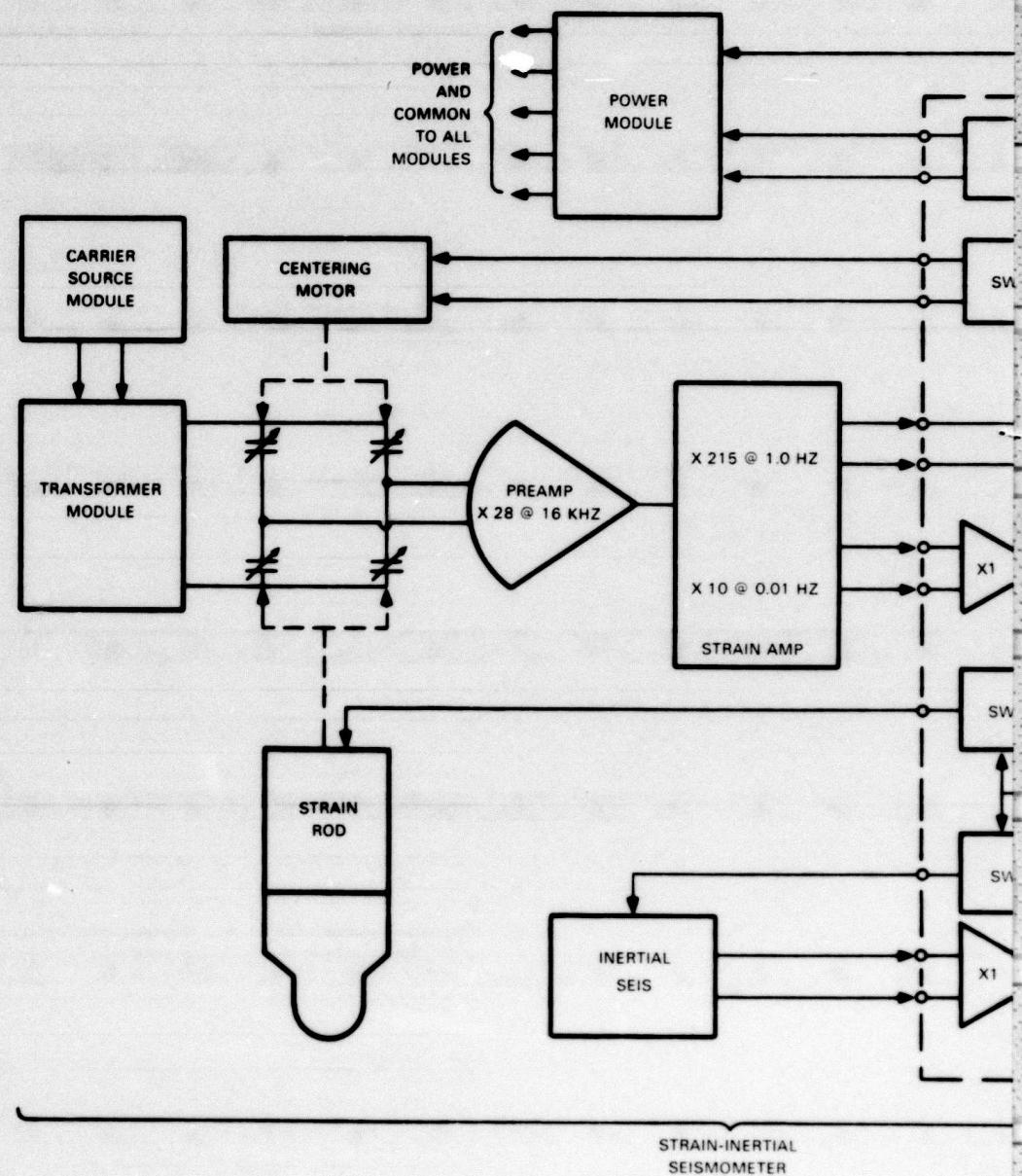
System ground originates at a copper ground stake near the surface equipment and connects to the ground bus of the wellhead terminal. Ground is carried to the strain-inertial seismometer in the borehole through the metal shield of the seis cable. The seismometer case is also grounded through the metal structure of the borehole casing.

5.3 INERTIAL SIGNAL CHANNEL

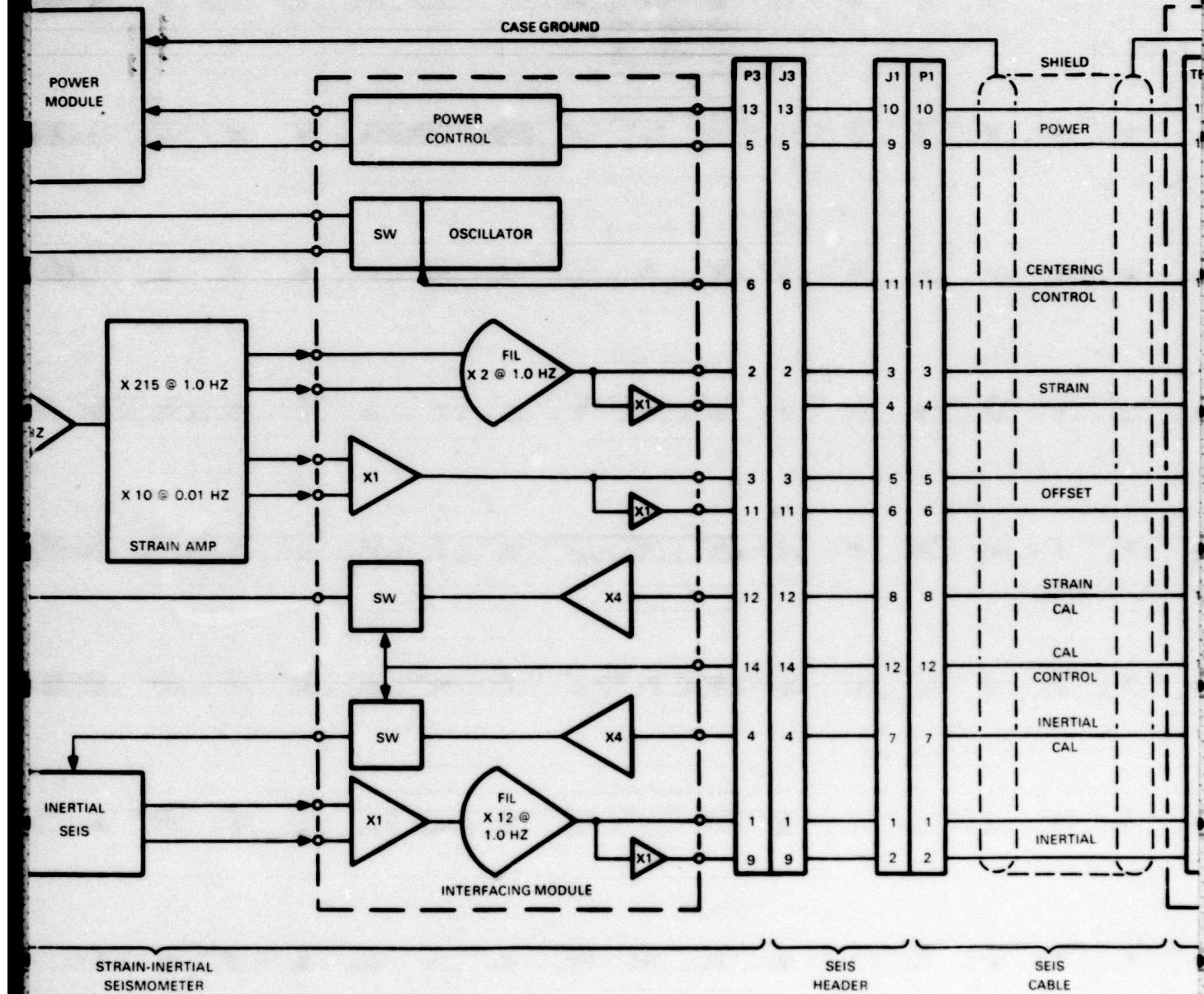
The output signal from the inertial seismometer is connected to the interfacing module of the strain-inertial seismometer where it is amplified, filtered, and converted into a balanced voltage signal for transmission up-hole to the wellhead terminal. There, additional amplification and filtering are accomplished to produce an output signal for connection to external recording equipment.

Responses at various points in the inertial signal channel are presented as follows:

1. Figure 11 - frequency response at the output of the inertial seismometer (volts/meter).
2. Figure 12 - frequency response at the output of the interfacing module (volts/meter).
3. Figure 13 - frequency response at the output of the wellhead terminal (volts/meter).
4. Figure 14 - frequency response at the output of the wellhead terminal (volts/meter/second).



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FIGURE

(1)

(2)

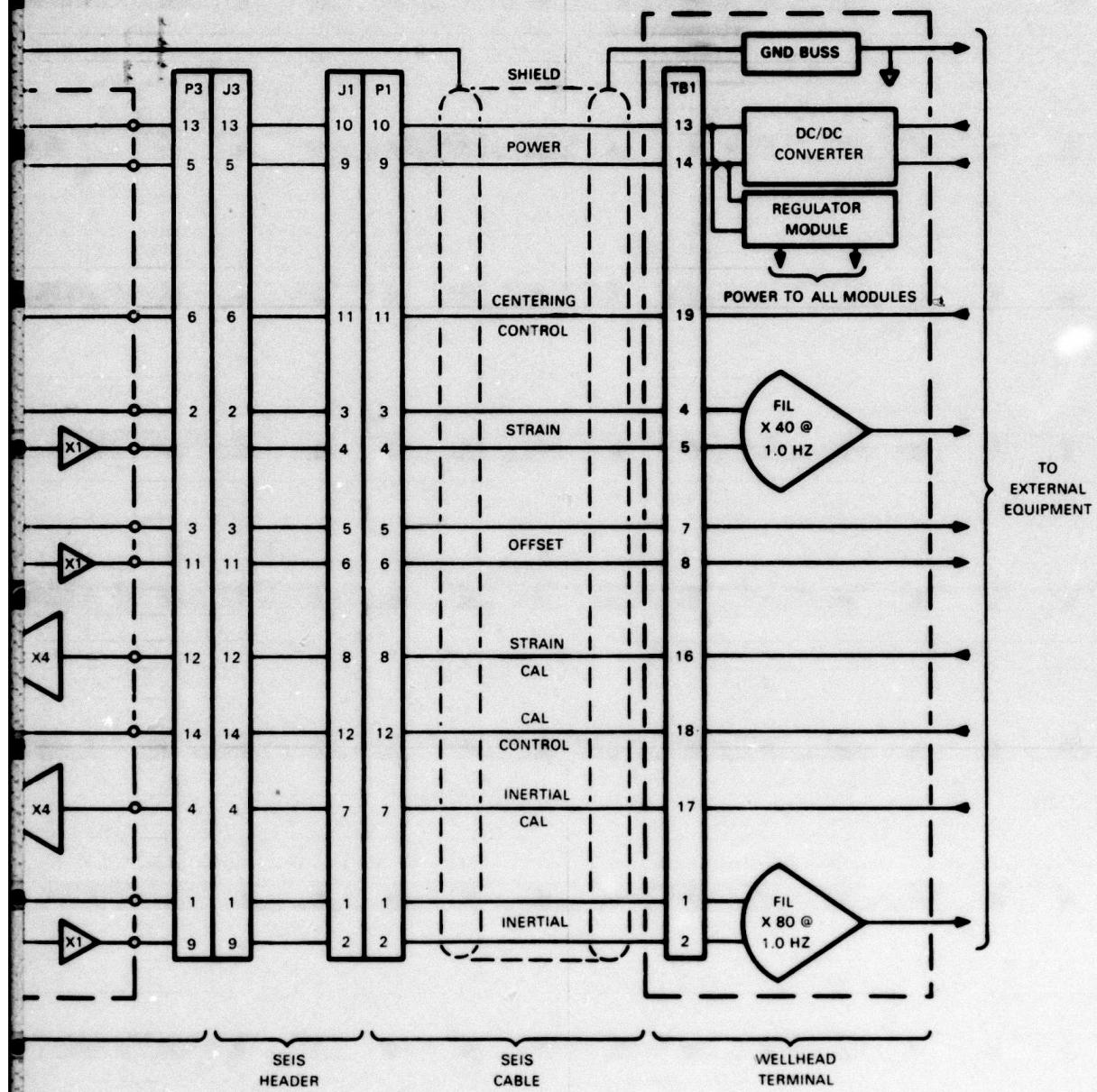


FIGURE 10. BLOCK DIAGRAM OF THE STRAIN-INERTIAL
SYSTEM ELECTRONICS

G 14454

5-3/4

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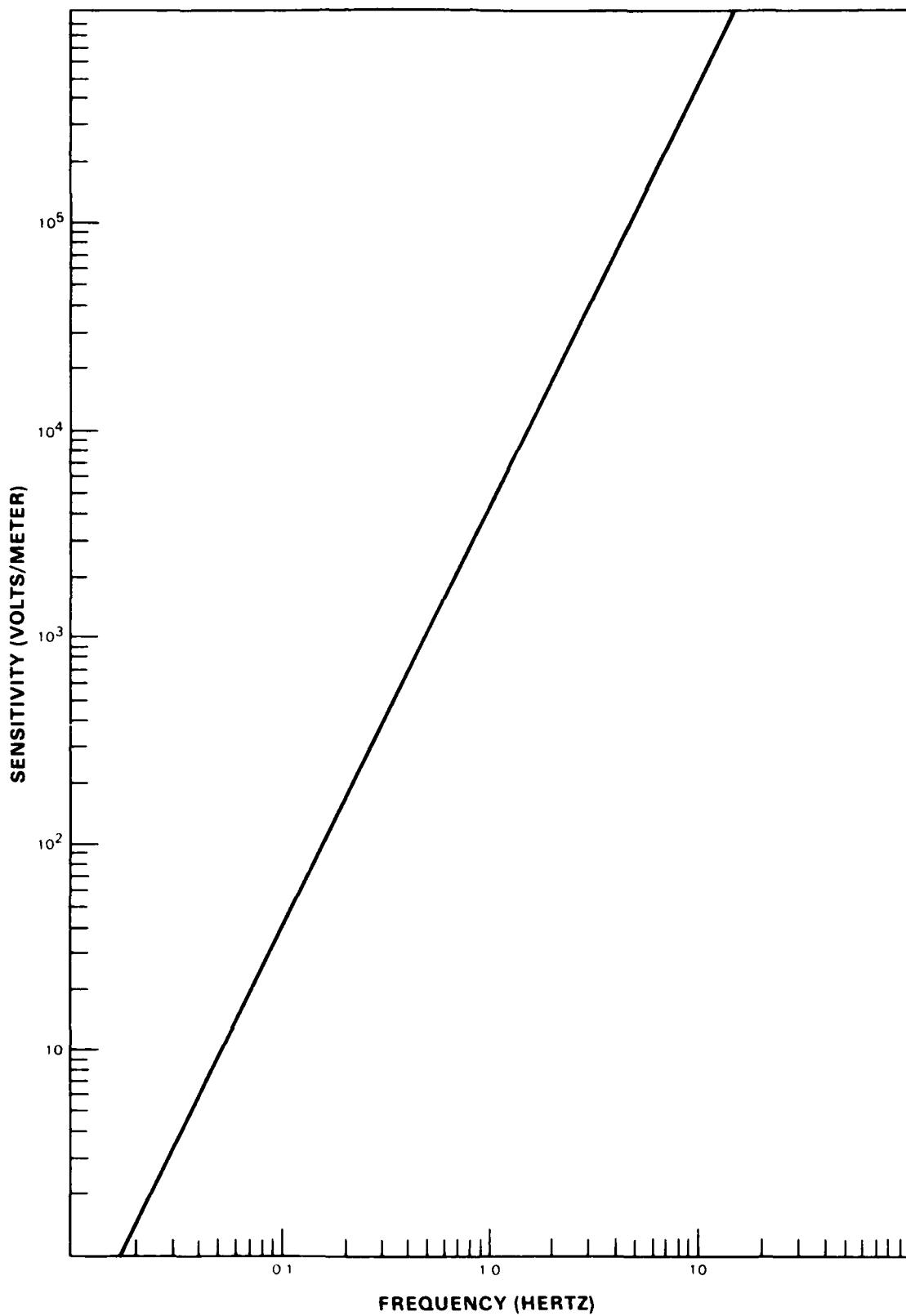


FIGURE 11. FREQUENCY RESPONSE OF THE INERTIAL CHANNEL AT THE OUTPUT OF THE
INERTIAL SEISMOMETER

G 14460

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370/29

TR 83-9

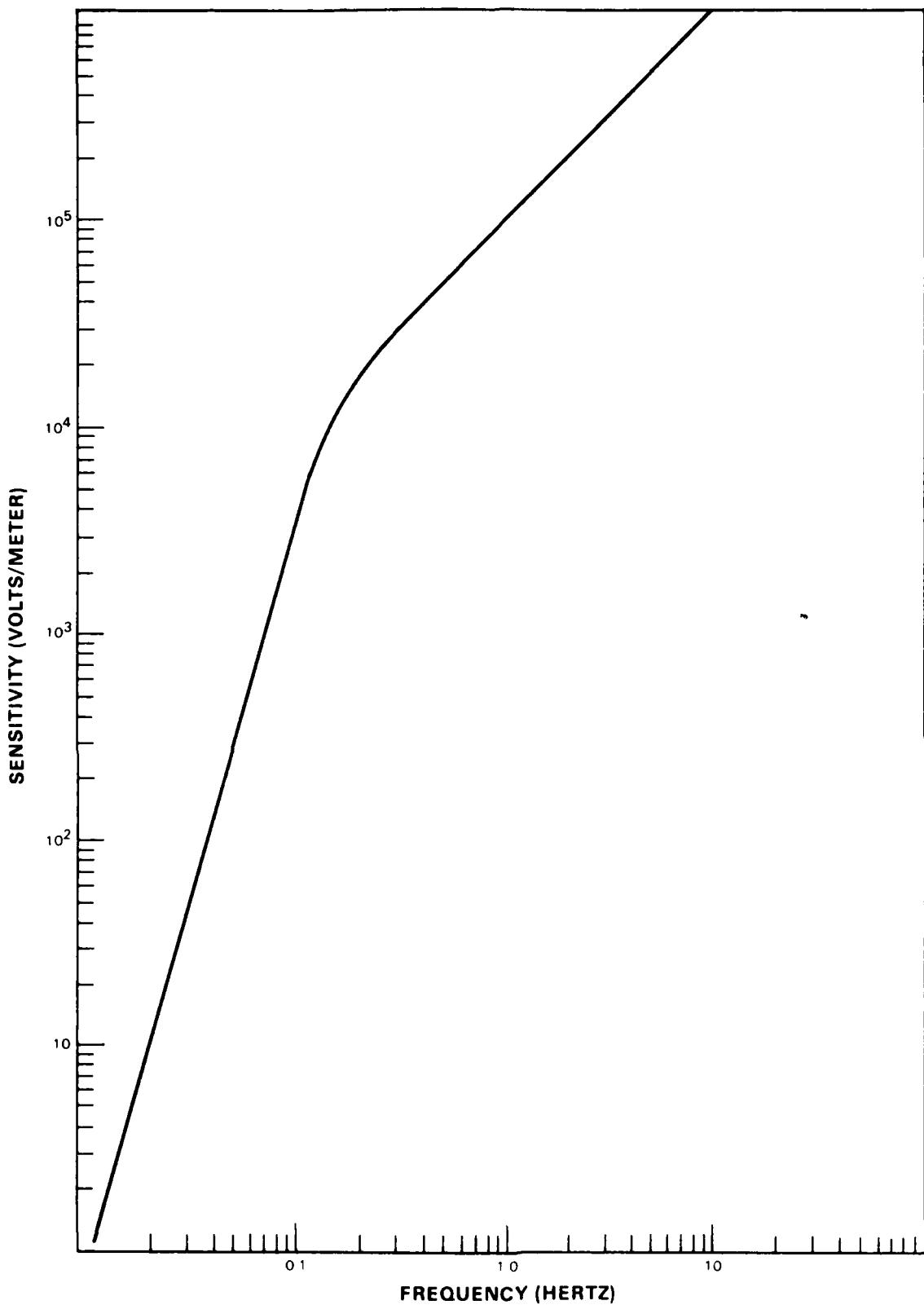


FIGURE 12. FREQUENCY RESPONSE OF THE INERTIAL CHANNEL AT THE OUTPUT OF THE
INTERFACING MODULE

G 14461

5-6

TR 83-9

370/30

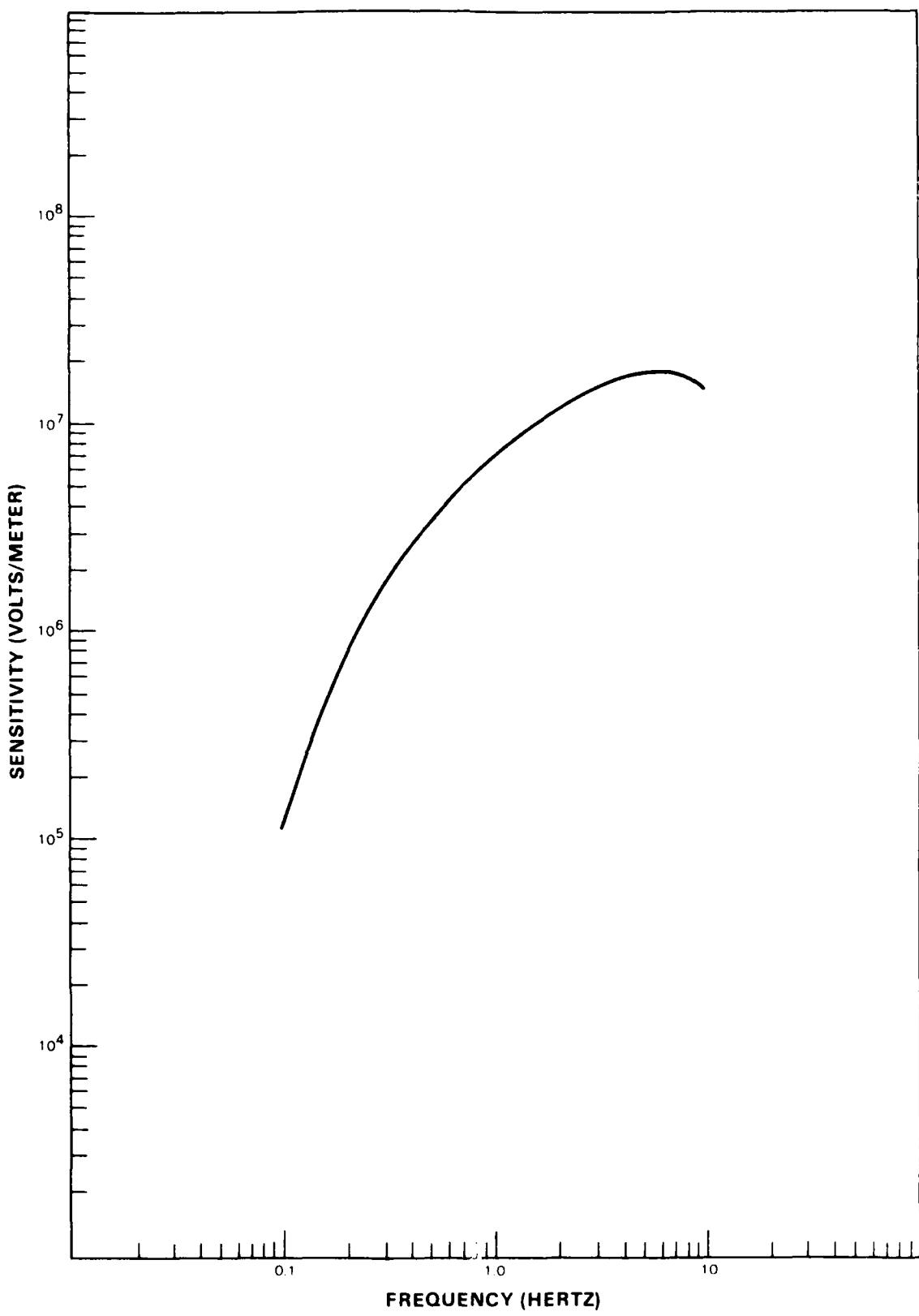


FIGURE 13 FREQUENCY RESPONSE (DISPLACEMENT) OF THE INERTIAL CHANNEL
AT THE OUTPUT OF THE WELLHEAD TERMINAL

5-7

370/31

TR 83-9

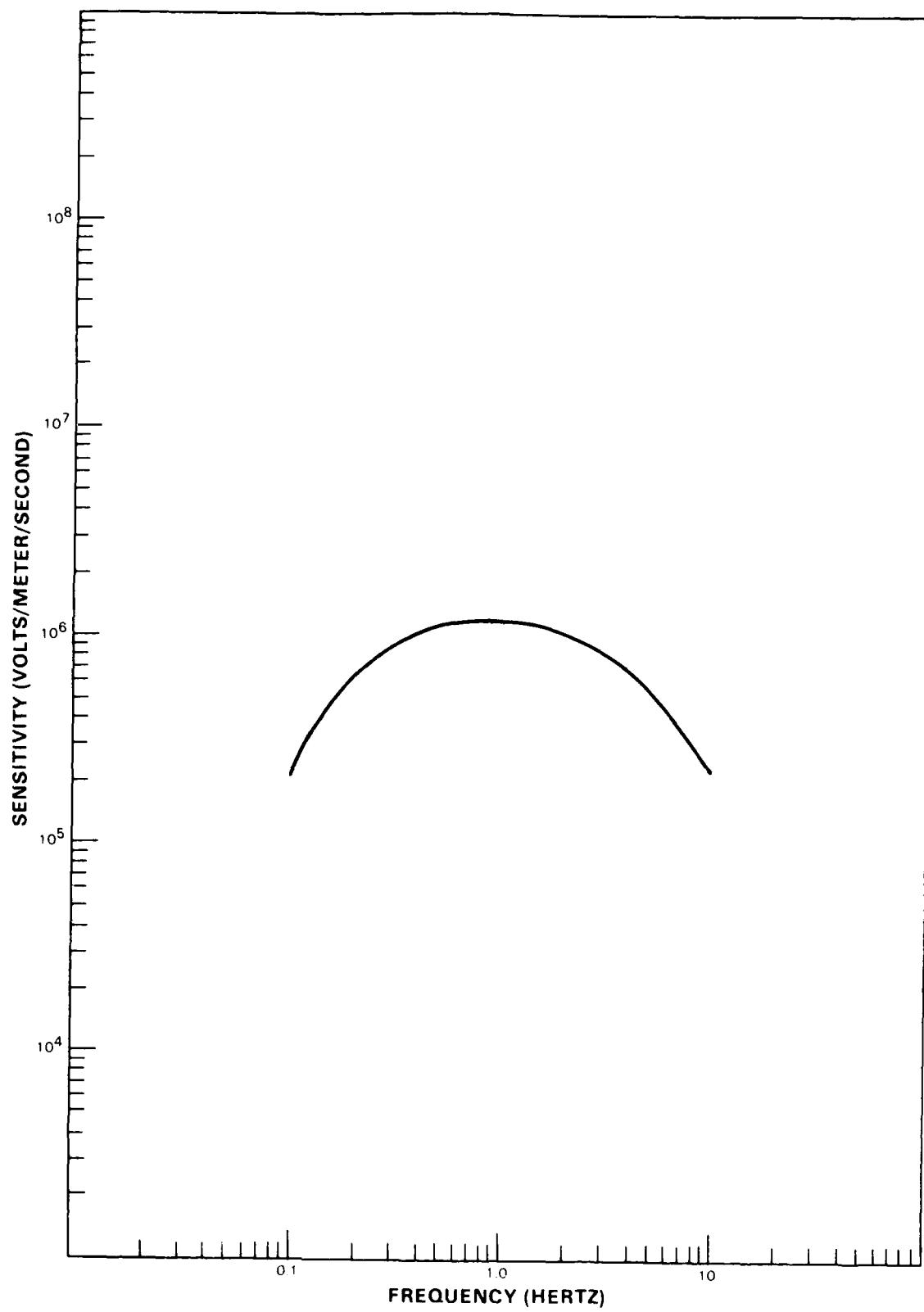


FIGURE 14 FREQUENCY RESPONSE (VELOCITY) OF THE INERTIAL CHANNEL
AT THE OUTPUT OF THE WELLHEAD TERMINAL

G 14456

5-8

TR 83-9

370/32

5.4 STRAIN SIGNAL CHANNEL

The strain signal originates in a capacitive Wheatstone bridge driven at a carrier frequency of 15,625 hertz. The carrier signal is produced by the carrier source module and is delivered to the strain bridge through the transformer module. Two elements of the strain bridge are controlled by the centering motor and are stationary during operation.

The remaining two elements of the strain bridge are controlled by earth strain through the strain rod, producing an amplitude-modulated carrier signal at the output of the bridge. The sensitivity of the bridge is 9000 volts rms (carrier) per meter (earth strain over a one-meter interval).

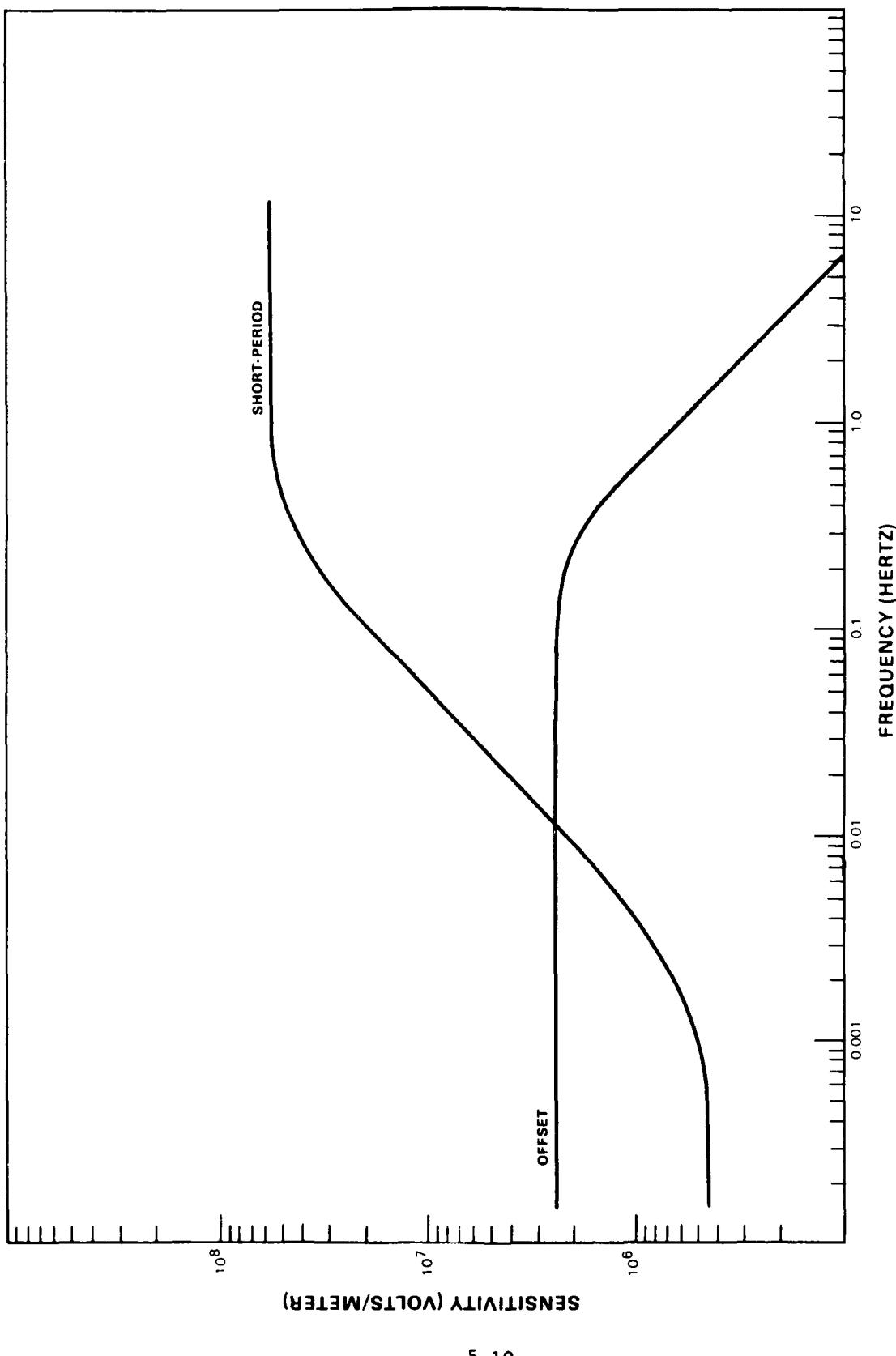
The strain bridge output signal is routed to an ultra low-noise preamp module which has a gain factor of 28 at the carrier frequency. The preamp output is connected to the strain amplifier which provides amplification, filtering, and carrier/analog conversion. The conversion sensitivity is 1 volt analog per 1 volt rms carrier. The strain amplifier produces two outputs; a high-gain short-period seismic signal and a low-gain offset signal which provides a long-term measure of the strain bridge balance. The offset signal also contains a long-period seismic signal component which may prove useful in the future.

The offset output of the strain amplifier is converted to a balanced signal in the interfacing module of the strain-inertial seismometer and transmitted up-hole to the wellhead terminal for connection to an external test unit.

The short-period output of the strain amplifier is fed to the interfacing module which provides amplification, filtering and conversion to a balanced signal for transmission up-hole to the wellhead terminal. Additional amplification and filtering are accomplished in the wellhead terminal to produce a short-period output signal for connection to external recording equipment.

Responses at various points in the strain signal channel are presented as follows:

1. Figure 15 frequency responses at the output of the strain amp (volts/meter).
2. Figure 16 frequency responses at the output of the interfacing module (volts/meter).
3. Figure 17 frequency response of the short-period channel at the output of the wellhead terminal (volts/meter).



TR 83-9

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FIGURE 15. FREQUENCY RESPONSES OF THE STRAIN CHANNEL AT THE OUTPUT OF THE STRAIN AMP

G 1445

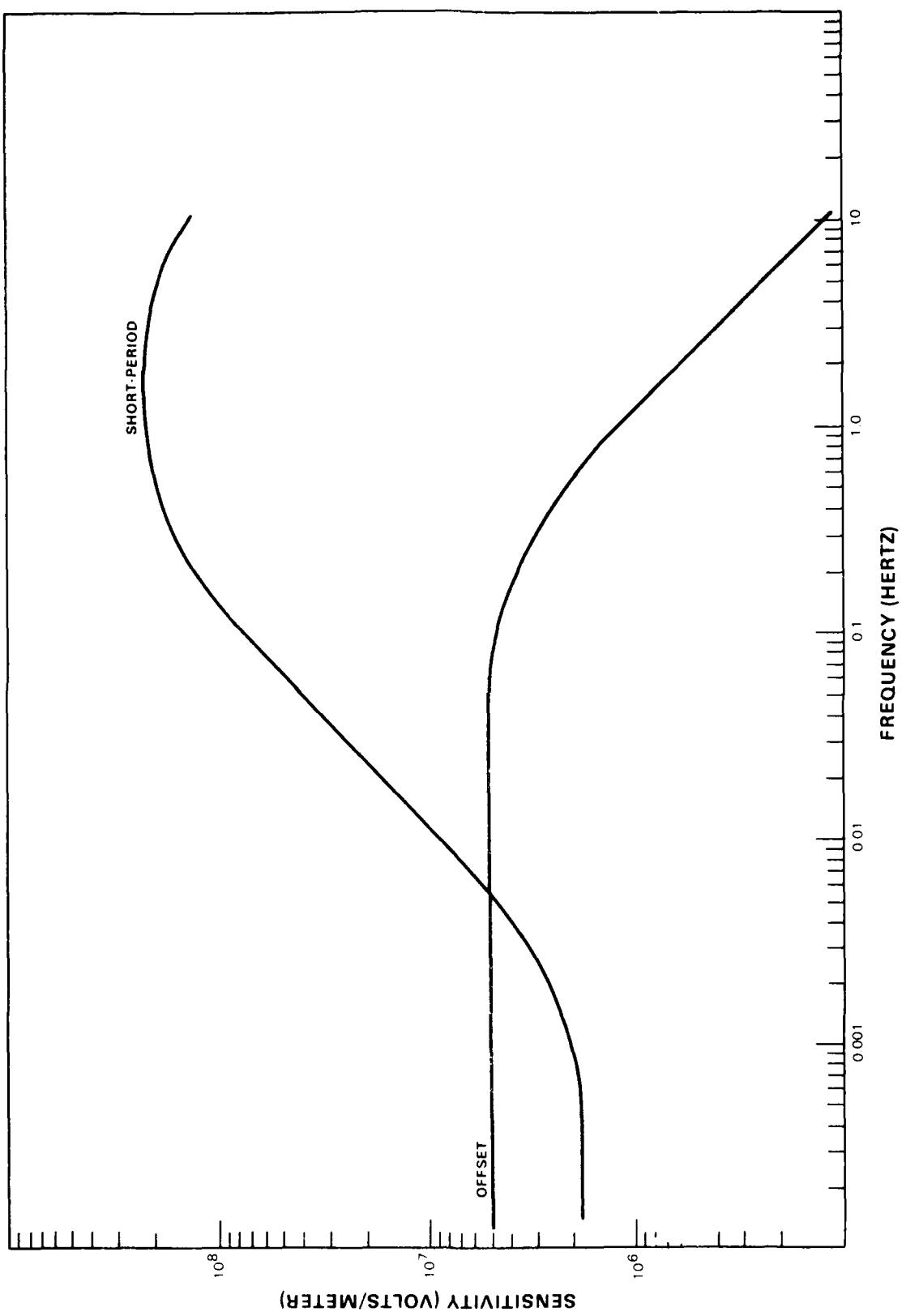


FIGURE 16. FREQUENCY RESPONSES OF THE STRAIN CHANNEL AT THE OUTPUT OF THE INTERFACING MODULE

G 14458

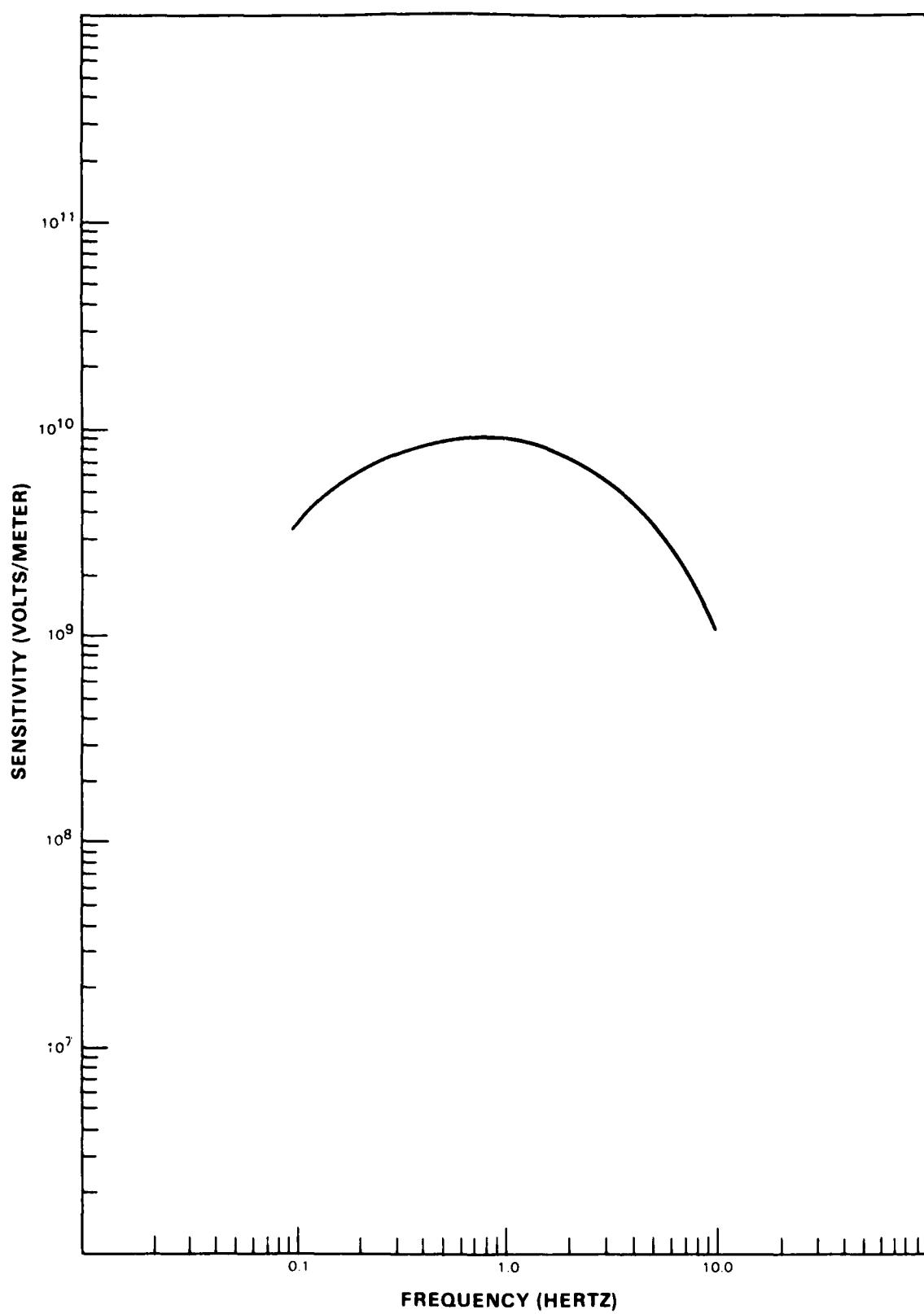


FIGURE 17. FREQUENCY RESPONSE OF THE STRAIN CHANNEL AT THE OUTPUT OF THE WELLHEAD TERMINAL

G 14459

5-12

TR 83-9

370/36

5.5 STRAIN-INERTIAL CALIBRATION

Three downhole signal conductors are used to calibrate the strain-inertial seismometer. The functions of these three circuits and their terminal points in the wellhead terminal are as follows:

Cal Control TBL-18
Strain Cal TBL-16
Inertial Cal TBL-17

All three of these circuits are activated by signals from an external test unit.

In normal operation, both the strain and inertial calibration circuits are switched off in the interfacing module of the strain-inertial seismometer to avoid the possibility of injecting noise into the system. When a plus 15 volt dc signal is applied to the cal control circuit, the strain cal circuit is activated; a minus 15 volt dc signal activates the inertial cal circuit.

When the strain cal circuit is activated, a sinusoidal voltage applied to the strain cal circuit at the wellhead terminal will be amplified in the interfacing module of the strain-inertial seismometer and routed to the strain calibrator installed in the base of the strain rod. This calibrator consists of a coil-magnet system which applies a force (proportional to the cal voltage) across a thin-wall section of the strain rod. This force causes an actual change in length of the strain rod and is registered by the strain bridge.

The calibration of the strain channel is governed by the following relationship:

$$Y_s = .210 V_s$$

where: Y_s = Equivalent earth strain in nanometers peak-to-peak

V_s = Wellhead calibration voltage in volts peak-to-peak

A standard strain magnification calibration has been adopted

where: $V_s = 2.38$ volts peak-to-peak at 1.0 hertz

$Y_s = 0.50$ nanometers peak-to-peak at 1.0 hertz

When the inertial cal circuit is activated, a sinusoidal voltage applied to the cal circuit at the wellhead terminal will be amplified in the interfacing module of the strain-inertial seismometer and routed to the inertial seismometer.

The calibration of the inertial channel is governed by the following relationship:

$$Y_I = \frac{1600}{f} V_I$$

where: Y_I = Equivalent earth displacement in nanometers peak-to-peak

V_I = Wellhead calibration voltage in volts peak-to-peak

f = Calibration frequency in hertz

A standard inertial magnification calibration has been adopted where

V_I = 0.20 volts peak-to-peak at 1.0 hertz

Y_I = 320 nanometers peak-to-peak at 1.0 hertz

Frequency responses of both the inertial and strain systems are produced using these standard calibration voltages at eight points in the frequency range from 0.2 to 10.0 hertz.

5.6 CENTERING CONTROL

Balancing of the strain bridge is accomplished by a bidirectional motor which controls two elements of the bridge. An external test unit is used to apply a centering control signal of plus or minus 15 volt dc to TBl-19 of the wellhead terminal. This signal activates an oscillator in the interfacing module and connects the oscillator output to the centering motor. The polarity of the control signal determines the direction of rotation of the centering motor.

6. STRAIN-INERTIAL FIELD TESTS

6.1 GENERAL

The Southern Methodist University seismological site (MCK) at McKinney, Texas, was selected for testing the strain-inertial seismometer system based on the analysis of noise data collected at the site in late 1980.

The installation of two boreholes for the strain-inertial system tests was completed in June 1982, and the strain-inertial seismometers were installed the next month. Preliminary tests were completed in August 1982, when final system tests were begun.

During these tests, the strain-inertial seismometers proved to be very field worthy. No serious problems were encountered, with the exception of excessive instrument noise levels.

6.2 PRELIMINARY TESTING

After installation, the system was allowed to stabilize for approximately ten days for the attenuation of system noise arising from thermal gradients, air convection, and mechanical relaxation. After stabilization, final adjustments of the system grounding and power circuits were accomplished to minimize any effect of these circuits on the system signals. Because the system involves multiple power regulation points plus two ground points (one at the borehole and one at the instrument trailer), these adjustments required considerable care.

Initial operation of the amplification, calibration and recording equipment revealed a major problem in the digital tape recording system. The recording system was returned to the lab for repair. Analysis indicated that excessive temperature within the module basket was the cause of the failure. A procedure to allow an hour of air-conditioned cooling prior to turn-on of the recording system was initiated. Several minor repairs to the system equipment were required during preliminary testing.

Work was then continued to conduct special tests and to establish operating procedures and parameters for the system, including the following items:

1. System recording levels
2. Recording procedures
3. Recording logs
4. System calibration levels
5. Frequency response levels

6. Calibration procedures
7. Data filter shaping
8. Difference trace networks
9. Phase shift networks.

During a period of preliminary recording and data analysis which followed, an excess noise level was identified in the strain outputs. Strain-inertial seismometer number 1 was returned to the lab where testing revealed quadrature voltage from the strain bridge to be the probable cause of the noise. The quadrature voltage is a signal 90° out of phase with the carrier signal which drives the strain detection bridge. The strain bridge was designed to be a balanced capacitive voltage divider network. The quadrature voltage arises as a result of one or more noncapacitive imbalance effects in the bridge. A trace of second and third harmonic voltage was also seen in the bridge output, probably due to the same imbalance effects.

A simple compensation circuit was added to the bridge which reduced the quadrature voltage. High ambient earth background motion and environmental disturbances in the lab would not allow an evaluation of the modification, so the seismometer was returned to the field site. Its performance had improved; however, substantial noise remained.

A review of the results of these preliminary tests led to the conclusion that the general operation of the strain-inertial system was acceptable and that future effort should be focused on the remaining major problem of excess system noise.

6.3 FINAL TESTING

During preliminary testing in 1982, the operation of the strain-inertial seismometers proved to be adequate in all respects except the excess system noise level. The major thrust of the final tests and the associated instrument modifications during 1982 and 1983 was to identify and eliminate the sources of this excess noise.

A "blocked-transducer" test, based on the use of an advanced plastic damping material, was performed on strain-inertial seismometer No. 1 at the McKinney test site in early September 1982. This test appeared to confirm that the noise problem existed within the strain measuring portion of the instrument. Figure 18 shows the results of a coherence test that was conducted at this time. Seismometer No. 1 was then returned to the lab.

The strain detection bridge was then reconfigured to a new design and tested. A single resistive element was found to be sufficient to eliminate quadrature voltage over the offset range of the instrument; however, the third harmonic distortion output from the bridge remained substantial. After a number of attempts, a successful solution to the harmonic problem was found by substituting a preamplifier circuit with much greater selectivity. Tests indicated that these modifications had improved the performance of the strain channel. Note that the coherence illustrated in figure 19 is better than that observed before modification (figure 18).

Strain-inertial seismometer No. 1 was returned to the McKinney test site in late September 1982, and, after settling, a number of tests were conducted. The results of these tests, including a coherence determination between strain 1 and strain 2, indicated a substantial improvement in the system noise level of strain-inertial seismometer No. 1.

Based on these findings, strain-inertial seismometer No. 2 was returned to the lab in early October and upgraded in the same manner as seismometer No. 1. It was then returned to the field for operational tests. After stabilization, a noise test record was produced on 27 October 1982 (digital tape MK09). Coherence tests were also conducted, and further improvements in coherence were observed as illustrated in figure 20.

While marked improvements in coherence had occurred as a result of the modifications, the strain systems were still registering noise from unknown sources. Three possible sources, and test procedures corresponding to each, were considered as outlined below.

1. Nonlinearities in the boreholes or in the instruments

If a noise signal were being generated as a result of nonlinearity, the noise would increase with signal amplitude. A difference trace (strain 2 - strain 1) was implemented on the chart recorder. Examination of the difference trace during the arrival of events did not indicate an increase in the noise.

2. Noise sources in surface portions of field systems

Narrow-band data filters and notch filters were designed and installed in both strain channels. A strain difference trace was implemented from these filtered outputs. With the system operating so that the difference trace could be monitored continuously, a number of tests of the surface systems were conducted as follows:

- a. System power variation
- b. System power filtering
- c. System grounding configuration
- d. Data cable connections
- e. Auxiliary function cable connections

None of these tests provided any measurable reduction in the system noise.

3. Active noise sources ("cement noise" and "fracture noise") in the borehole

A blocked-transducer test was performed on strain-inertial seismometer No. 2 during the first week in April 1983. The noise at the output of this seismometer was found to be comparable in amplitude and frequency distribution to the strain difference trace as recorded in previous tests. This result leads to the following notes:

- a. The major noise source was not in the borehole or in the instrument seating interfaces.
- b. Because the transducer was blocked and operating in a very quiet seismic environment, it can safely be assumed that the threshold noise did not result from direct transducer armature motion.

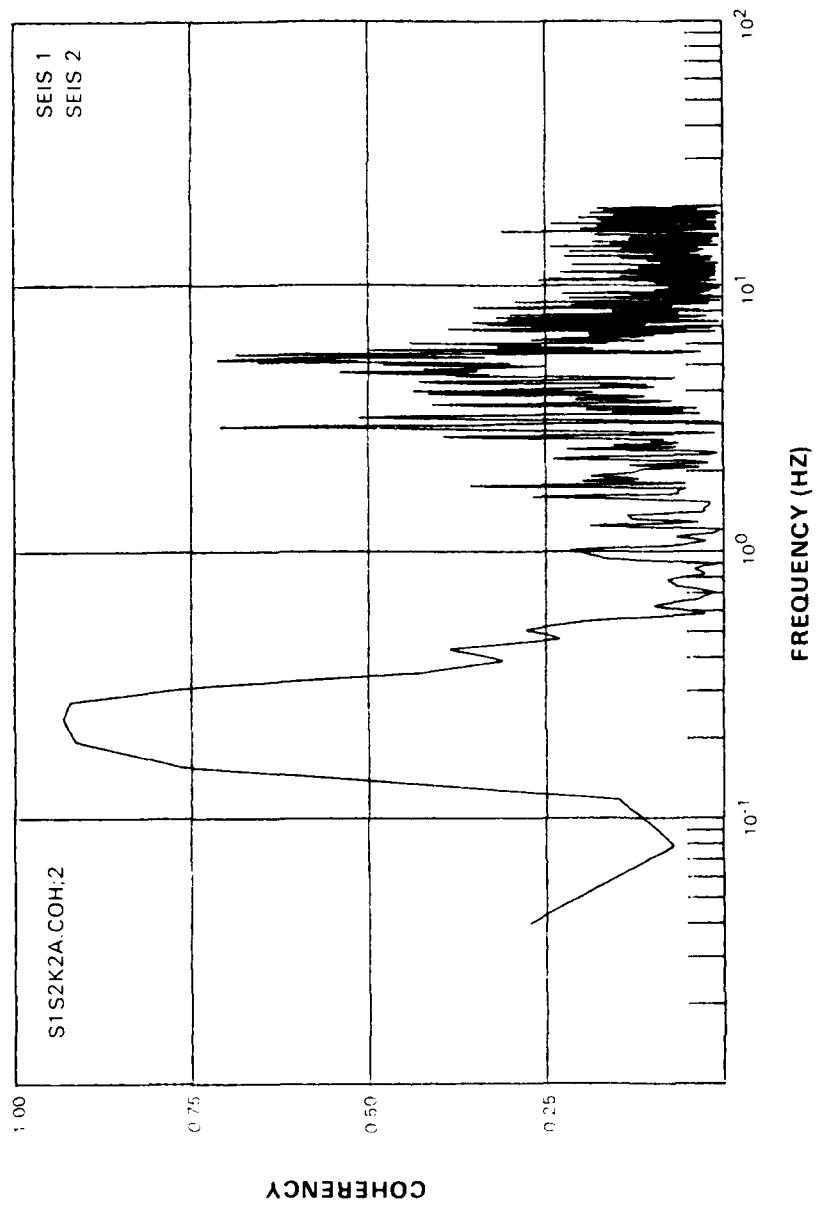


FIGURE 18. COHERENCE BETWEEN S1 AND S2 MK002A, 14 BLOCK AVERAGE
 (NEITHER INSTRUMENT MODIFIED)
 G14652

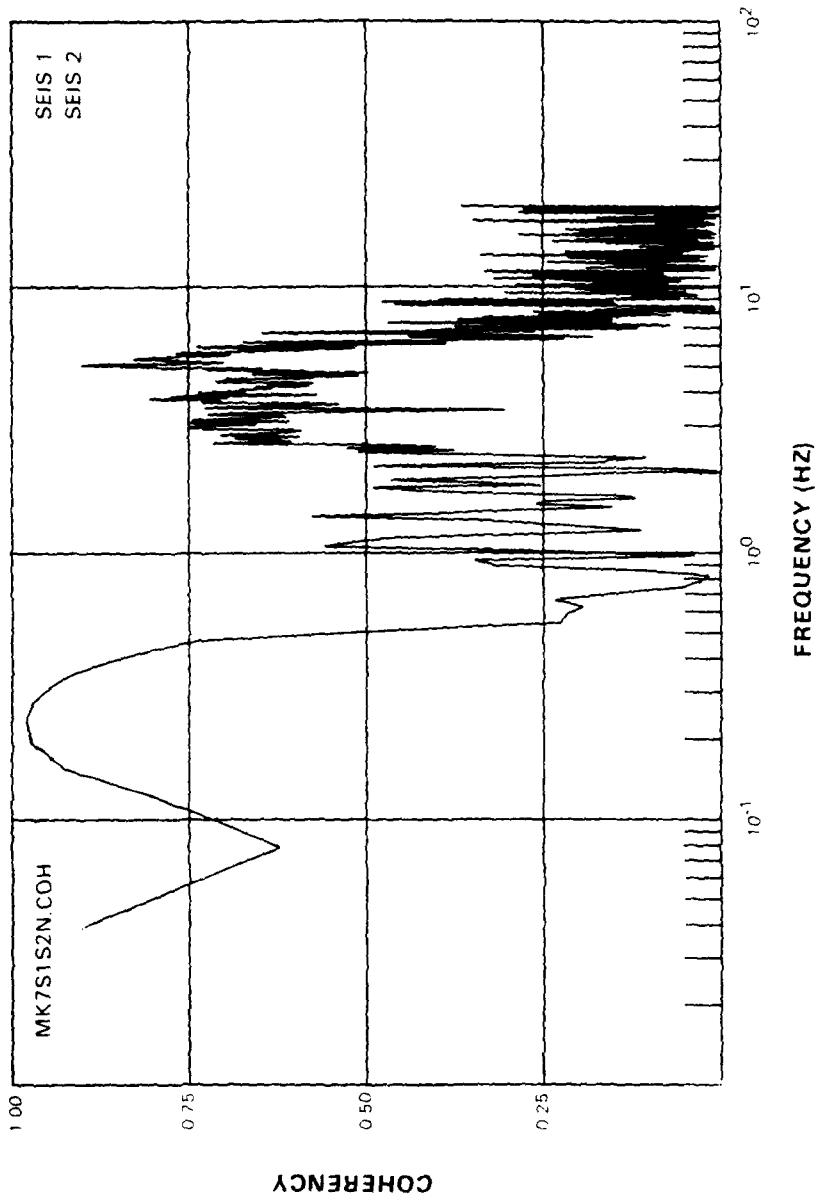


FIGURE 19. COHERENCE S1-S2 MK7 NOISE, 14 BLOCK AVERAGE (1024 PTS BLK)
(STRAIN SEISMOMETER NO. 1 MODIFIED)

G14661

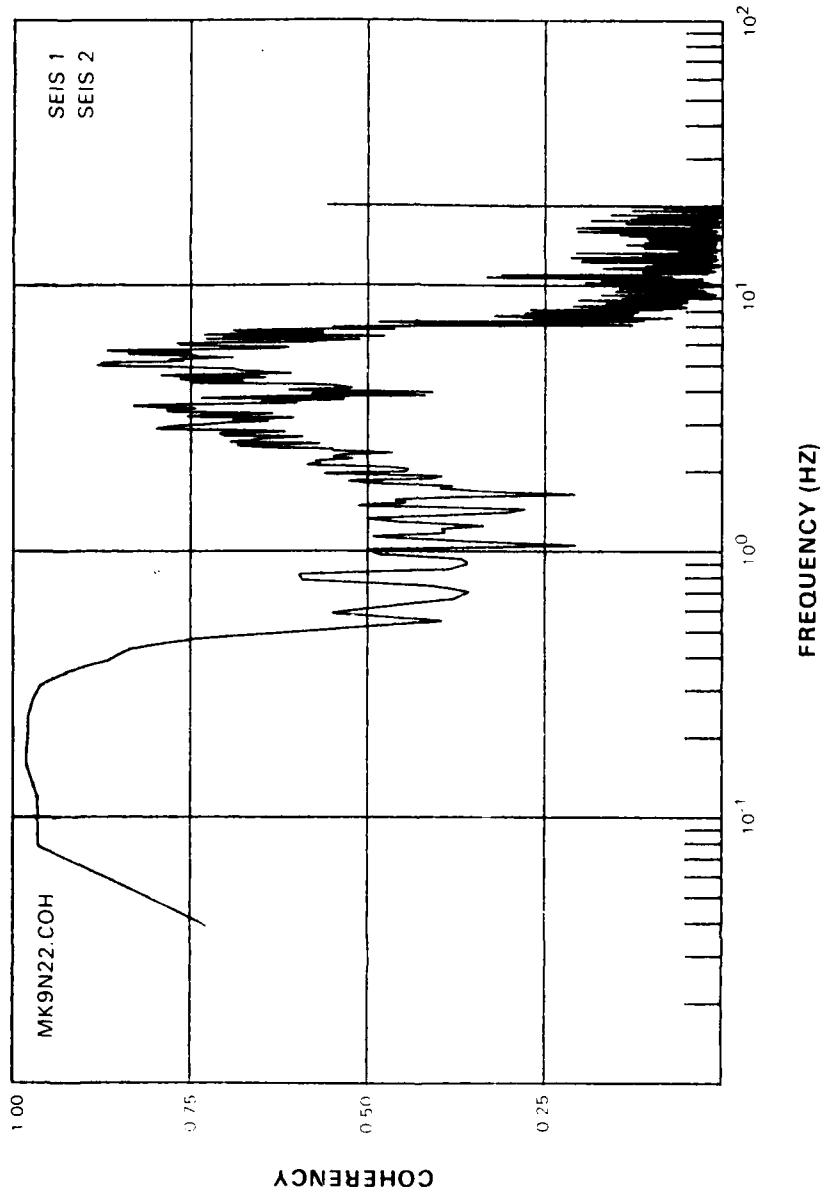


FIGURE 20. COHERENCE S1-S2 MI9 NOISE, 22 BLOCK AVERAGE (1024 PTS/BLK)
(BOTH INSTRUMENTS MODIFIED)

($\epsilon_1, \epsilon_2, \epsilon_3, \epsilon_4$)

- c. Multiple tests had been conducted previously indicating that the threshold noise source was not in the electronic circuits of the strain channel.
- d. The threshold noise source appeared to exist within the strain transducer-crystalline stress relaxation or an ionization process appear to be the major possibilities.

While the strain threshold noise is extremely low, it is believed that crystalline stress relaxation in a similar transducing system in the KS 36000 seismometer would have been discovered if this were the noise source.

An ionization process is precluded in the KS 36000 seismometer transducing system because the system is contained within a hard vacuum environment. The strain transducer system is contained in a helium environment, which is a very poor supporter of ionization; however, impurities in the gas plus residual traces of air from the backfilling procedure may play a part.

To investigate the strain transducer noise mechanism further, consideration was given to operating the transducer with an internal vacuum; however, there was considerable doubt that the O-ring seals in the strain transducer could maintain a hard vacuum. The most practical method for investigating the strain transducer noise mechanism appeared to be the replacement of the contained helium with a fluid which would not support ionization. A high-viscosity silicon fluid was selected.

Strain-inertial seismometer No. 2 was removed from the borehole, disassembled in the Garland lab, backfilled with silicon fluid, and returned to the field on 19 April, 1983 for further tests with the transducer blocked.

A number of minor problems occurred as a result of changing the dielectric medium in the strain transducer. A sequence of tests and modifications solved these problems, and, in late May 1983, a blocked transducer test was conducted and recorded on digital tape No. 22. A noise power spectrum from this tape is shown together with two previous incoherent noise spectra in figure 21. Filtered versions of the three spectra are shown in figure 22 to facilitate measurement of improvement ratios at various frequencies in the short-period band.

The improvement between the upper and middle traces in figure 21 was accomplished by a number of measures which eliminated quadrature and harmonic noise generated within the strain detection bridge.

It may be noted that both the upper and middle spectra exhibit a $1/f$ characteristic in the central portion of the frequency range. Additional investigations into the instrument noise level centered on possible mechanisms for this $1/f$ noise.

The improvement between the middle and lower traces in figure 21 was accomplished by eliminating ionization noise within the detection bridge and by increasing the damping of the strain-rod system.

The resulting lower spectra follows the instrument channel response to a good approximation, indicating that the present threshold is controlled by a white-noise source.

The overall improvement ratios measured between the upper and lower spectra in figure 22 are as follows:

<u>Frequency</u> <u>Hertz</u>	<u>Noise</u> <u>Improvement</u> <u>Ratio</u>
0.5	15/1
1.0	7/1
2.0	7/1
3.0	10/1
5.0	7/1

The results of these improvements are given in terms of seismic background to system noise ratios in the following table. These ratios are based on a comparison of the lower spectra in figure 22 with an earth background power spectra from digital tape MK17.

<u>Frequency</u> <u>Hertz</u>	<u>Seismic Background</u> <u>to System Noise Ratio</u>
0.5	45/1
1.0	8/1
2.0	4/1
3.0	16/1
5.0	16/1

Two additional modifications were made in an attempt to reduce the system noise further; however, no measurable improvement was noted. After the replacement of the calibration coil, which had been damaged during the extended blocked-transducer test period, strain-inertial seismometer No. 2 was reinstalled in the operating configuration to record earth background samples and seismic events.

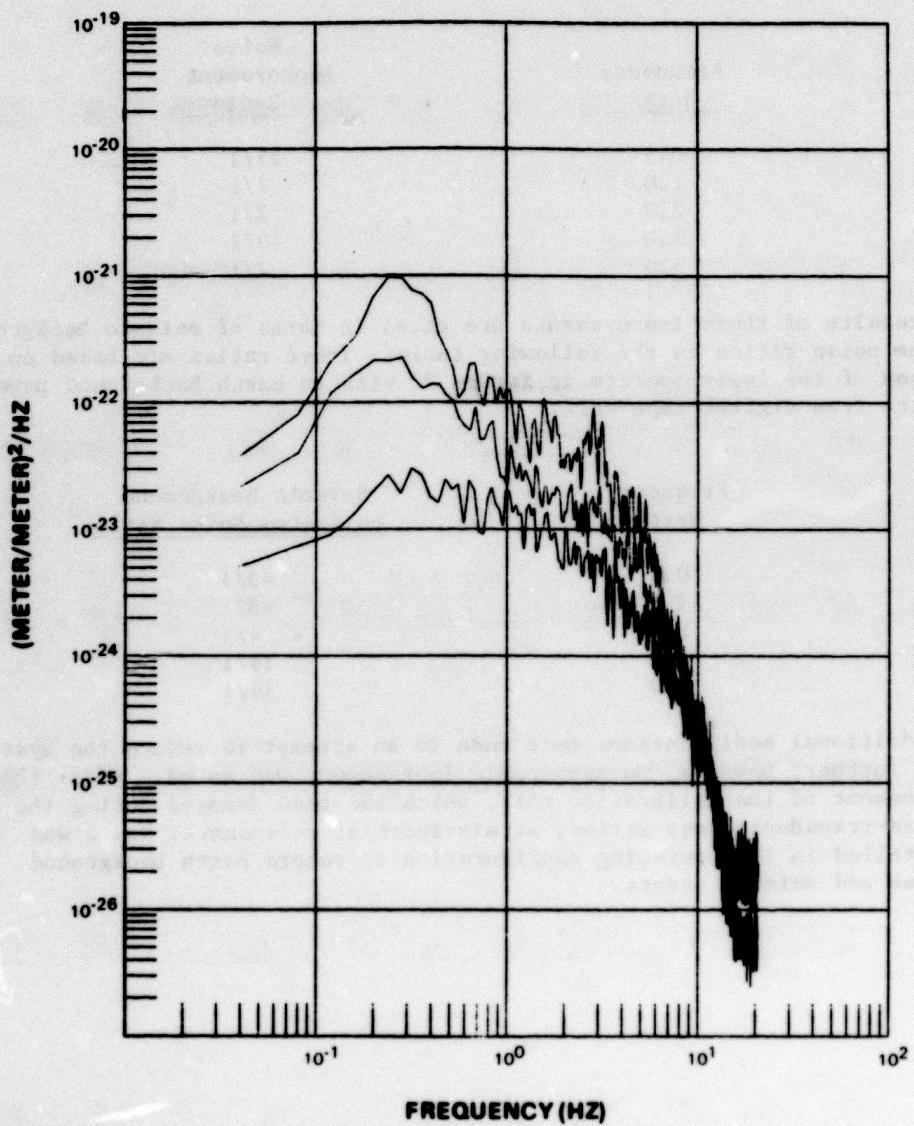


FIGURE 21. STRAIN-INERTIAL SYSTEM NOISE IMPROVEMENT SPECTRA (UNFILTERED)
UPPER TRACE - INCOHERENT NOISE SPECTRUM S2 TAPE 6C (13/1024)
MIDDLE TRACE - INCOHERENT NOISE SPECTRUM S2 TAPE 18 (20/1024)
LOWER TRACE - NOISE POWER SPECTRUM S2 TAPE 22 (9/1024)

G14653

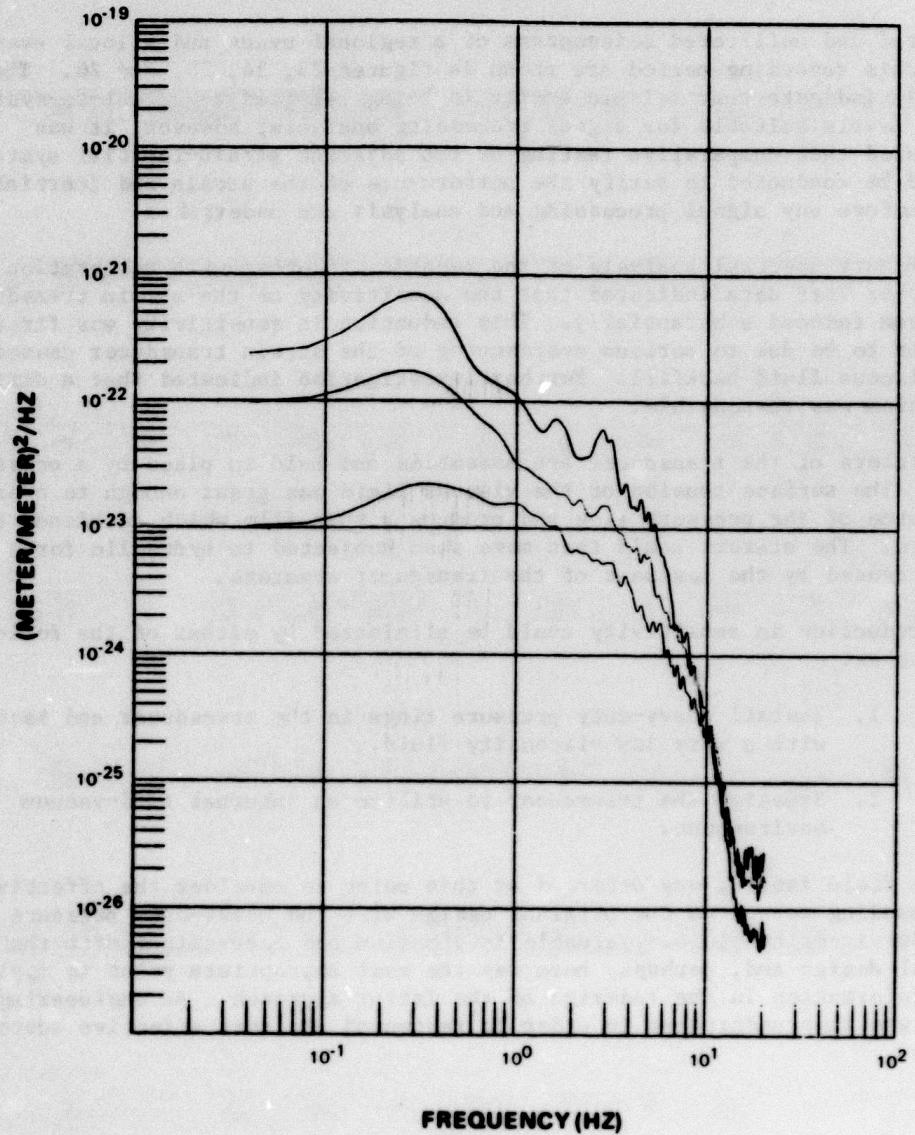


FIGURE 22. STRAIN-INERTIAL SYSTEM NOISE IMPROVEMENT SPECTRA (FILTERED)
UPPER TRACE - INCOHERENT NOISE SPECTRUM S2 TAPE 6C (13/1024)
MIDDLE TRACE - INCOHERENT NOISE SPECTRUM S2 TAPE 18 (20/1024)
LOWER TRACE - NOISE POWER SPECTRUM S2 TAPE 22 (9/1024)
(FILTER - HANNING 3-POINT, 11 ITERATIONS)

G14654

6.4 STRAIN-INERTIAL SEISMOGRAMS

Following reinstallation of strain-inertial seismometer No. 2, six digital tapes were recorded. These records provided strain data on seismic background during various environmental conditions and also data on several seismic events.

Filtered and unfiltered seismograms of a regional event and a local event from this recording period are shown in figures 23, 24, 25, and 26. These records indicate that seismic energy is being recorded at signal-to-system-noise levels suitable for signal processing analysis; however, it was concluded that comparative testing of two adjacent strain-inertial systems should be conducted to verify the performance of the strain and inertial sensors before any signal processing and analysis are undertaken.

Preliminary spectral analysis of the records, together with calibration data and other test data indicated that the sensitivity of the strain transducer had been reduced substantially. This reduction in sensitivity was first thought to be due to serious overdamping of the strain transducer caused by the viscous fluid backfill. Further investigation indicated that a different mechanism was responsible.

The stators of the transducer are assembled and held in place by a pressure ring. The surface tension of the viscous fluid was great enough to overcome the force of the pressure ring and produce a thin film which cushioned the stators. The stators could then move when subjected to hydraulic force in the fluid caused by the movement of the transducer armature.

This reduction in sensitivity could be eliminated by either of the following approaches:

1. Install heavy-duty pressure rings in the transducer and back-fill with a very low viscosity fluid.
2. Redesign the transducer to utilize an internal hard-vacuum environment.

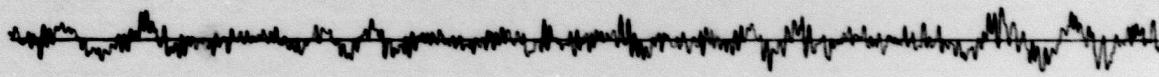
Active field testing was deferred at this point to consider the effectiveness of demanding more from the original design with the heavy-duty pressure rings and low-viscosity fluid. Valuable information had been gained with the original design and, perhaps, here was the most appropriate point to apply this information in the redesign of the latter approach. An engineering study was then undertaken in order to recommend the most effective course of action.

50:20.00 50:30.00 50:40.00 50:50.00 51:0.00 51:10.00 51:20.00

**17:50:20:00Z
22 JUNE 1963**



STRAIN 2 MAG = 11×10^7 @ 1.0 Hz



INERTIAL 2 MAG = 12×10^4 @ 1.0 Hz

400 SAMPLES/HORIZONTAL INCH
800 COUNTS/VERTICAL INCH
DIGITAL TAPE 25

6 - 13/14 ①

00 51:10.00 51:20.00 51:30.00 51:40.00 51:50.00 52:0.00 52:10.00 52:20.00

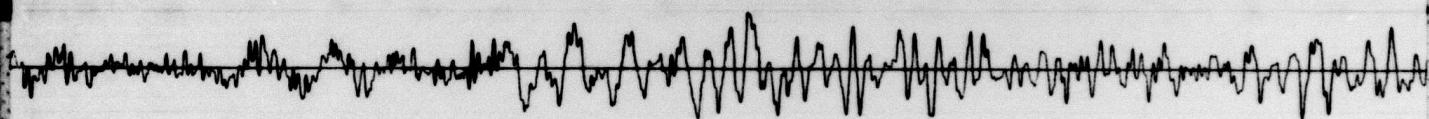
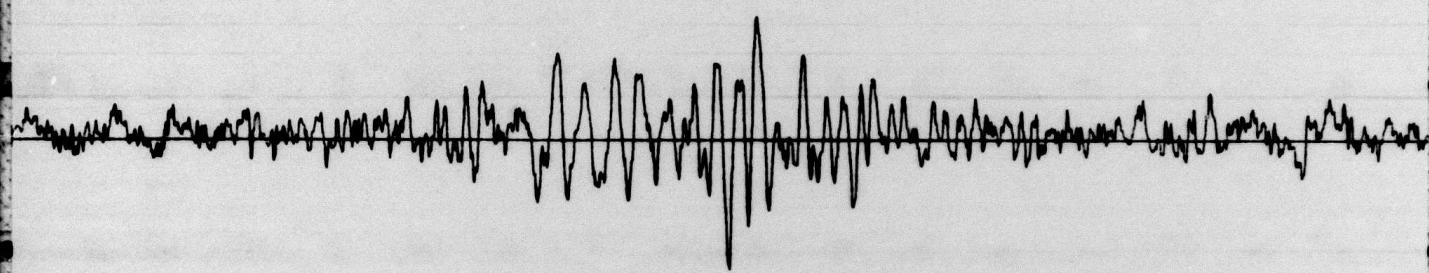


FIGURE 23. STRA
SEISM

(2)

1:50.00 52:0.00 52:10.00 52:20.00 52:30.00 52:40.00

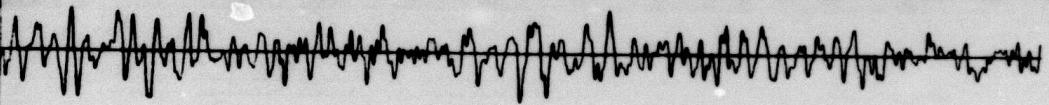
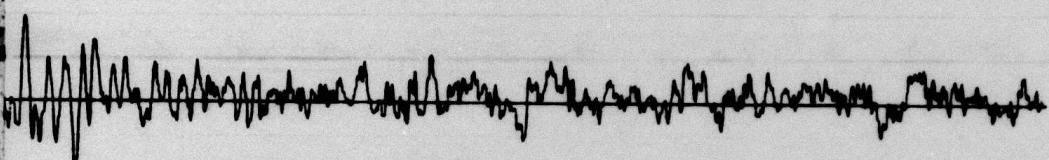


FIGURE 23. STRAIN-INERTIAL RECORDING OF REGIONAL
SEISMIC EVENT UNFILTERED DATA

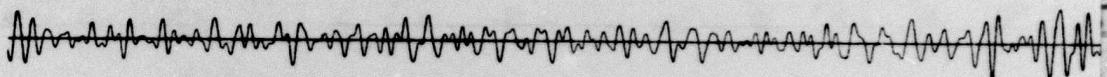
G14655

6-13/14

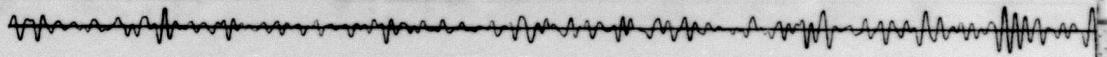
TR 83-9

50:20.00 50:30.00 50:40.00 50:50.00 51:0.00 51:10.00 51:20

17:50:20:00Z
22 JUNE 1963



STRAIN 2 MAG = 22×10^7 @ 1.0 Hz



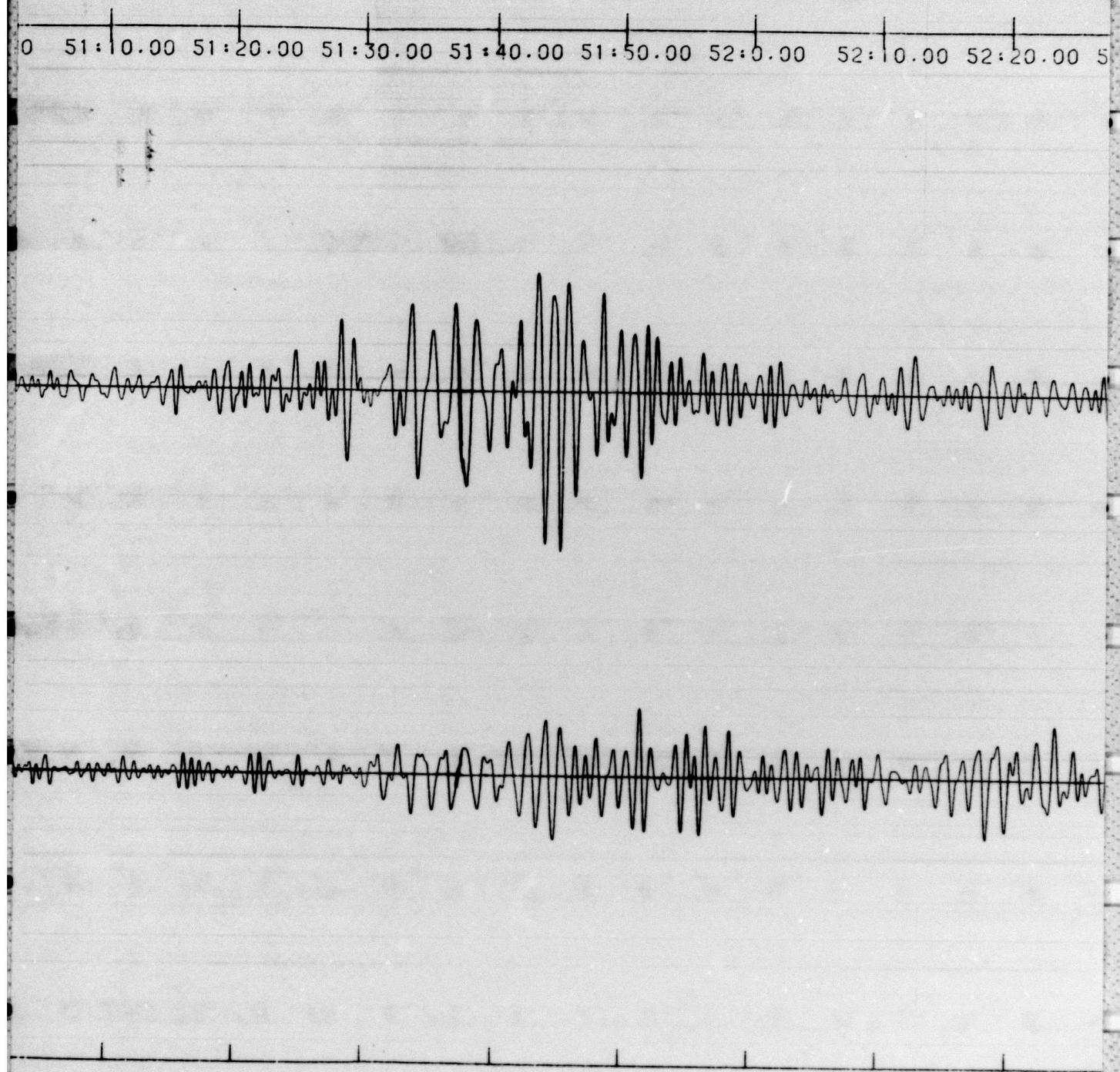
INERTIAL 2 MAG = 24×10^4 @ 1.0 Hz

400 SAMPLES/HORIZONTAL INCH
400 COUNTS/VERTICAL INCH
DIGITAL TAPE 25



6-15/16 TR 83-9

(1)



(2)

FIGURE 24. STRAIN-IN-E
SEISMIC EV
4 POLE

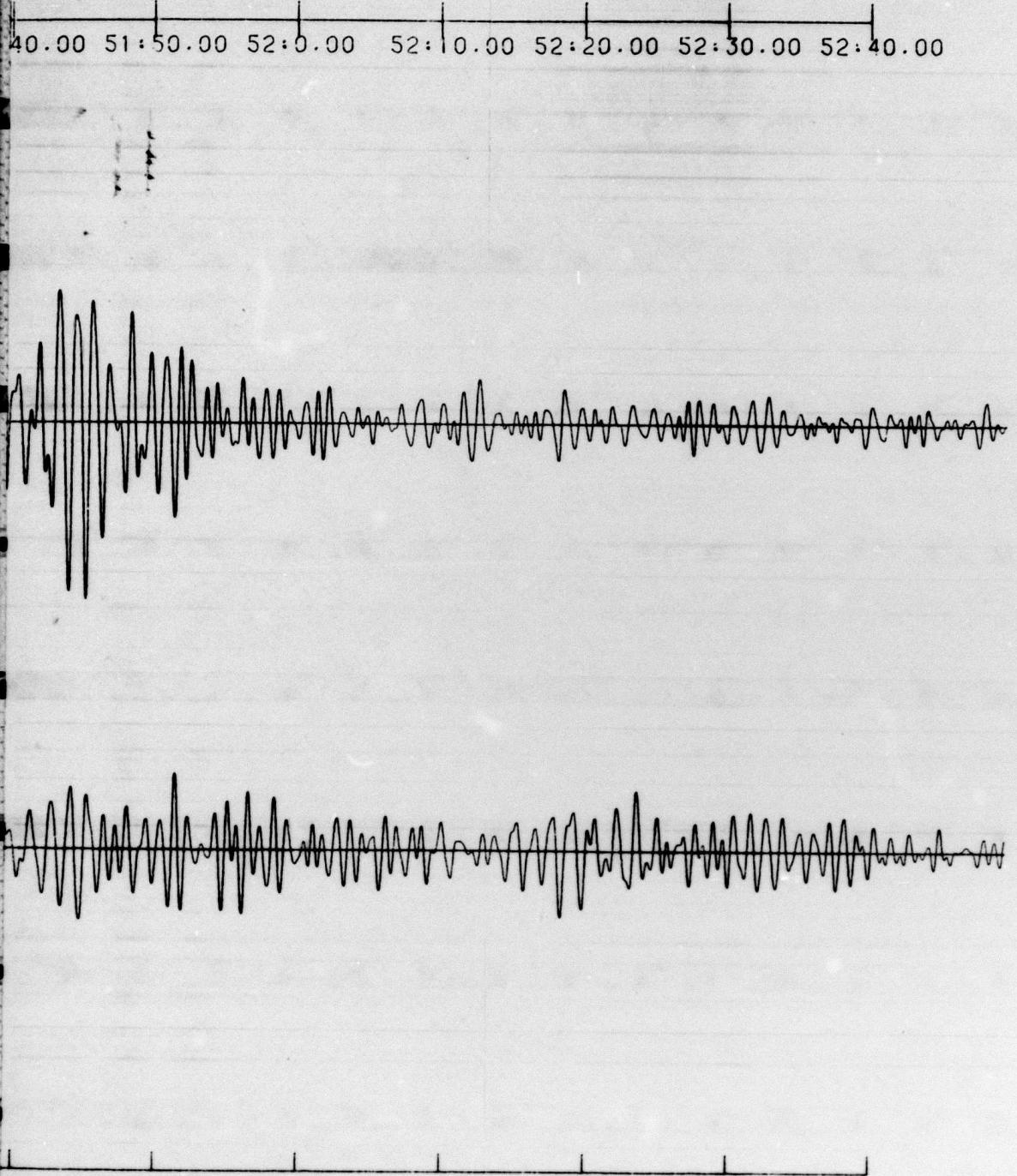


FIGURE 24. STRAIN-INERTIAL RECORDING OF REGIONAL
SEISMIC EVENT DATA FILTER, 0.5 - 2.0 HZ.
4 POLE

G14656

6-15/16

TR 83-9

21:36.00 21:46.00 21:56.00 22:6.00 22:16.00 22:26.00 22:36.00 22:

**16:21:36.00Z
23 JUNE 1983**



STRAIN 2 MAG = 12×10^7 @ 1.0 Hz



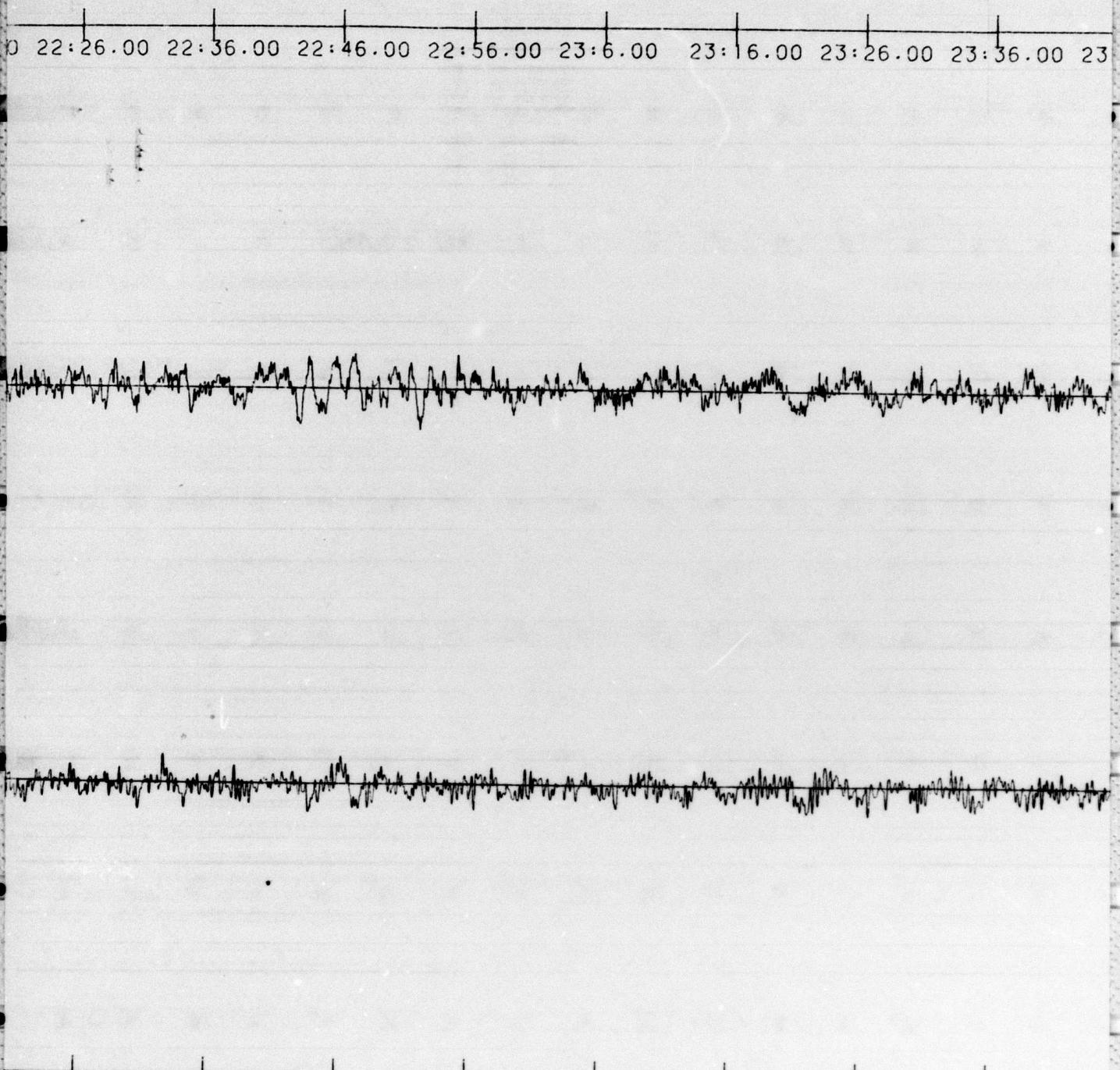
INERTIAL 2 MAG = 13×10^4 @ 1.0 Hz

400 SAMPLES/HORIZONTAL INCH
800 COUNTS/VERTICAL INCH
DIGITAL TAPE 25B

6-17/18

TR 83-9

①



(2)

FIGURE 25. S
S

23:6.00 23:16.00 23:26.00 23:36.00 23:46.00 23:56.00 24:6.00



FIGURE 25. STRAIN-INERTIAL RECORDING OF LOCAL
SEISMIC EVENT UNFILTERED DATA

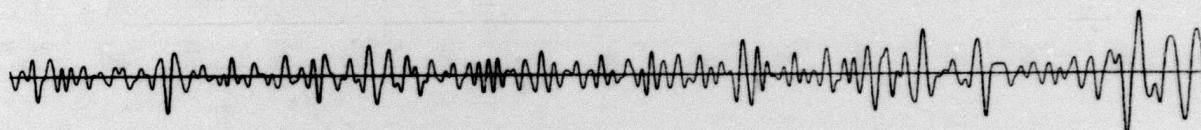
G14657

6-17/18

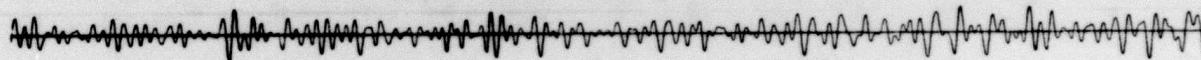
TR 83-9

21:36.00 21:46.00 21:56.00 22:6.00 22:16.00 22:26.00 22:36.00 22:46

**16:21:36.00Z
23 JUNE 1983**



STRAIN 2 MAG = 24×10^7 @ 1.0 Hz



INERTIAL 2 MAG = 26×10^4 @ 1.0 Hz

400 SAMPLES/HORIZONTAL INCH
400 COUNTS/VERTICAL INCH
DIGITAL TAPE 25B

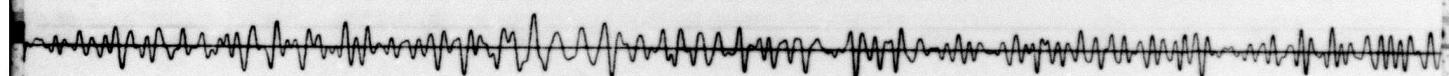
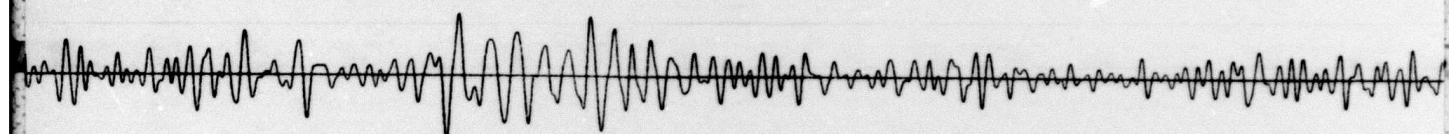


16 - 19/20

①

TR 83-9

.00 22:26.00 22:36.00 22:46.00 22:56.00 23:6.00 23:16.00 23:26.00 23:36.00



①

②

FIGURE

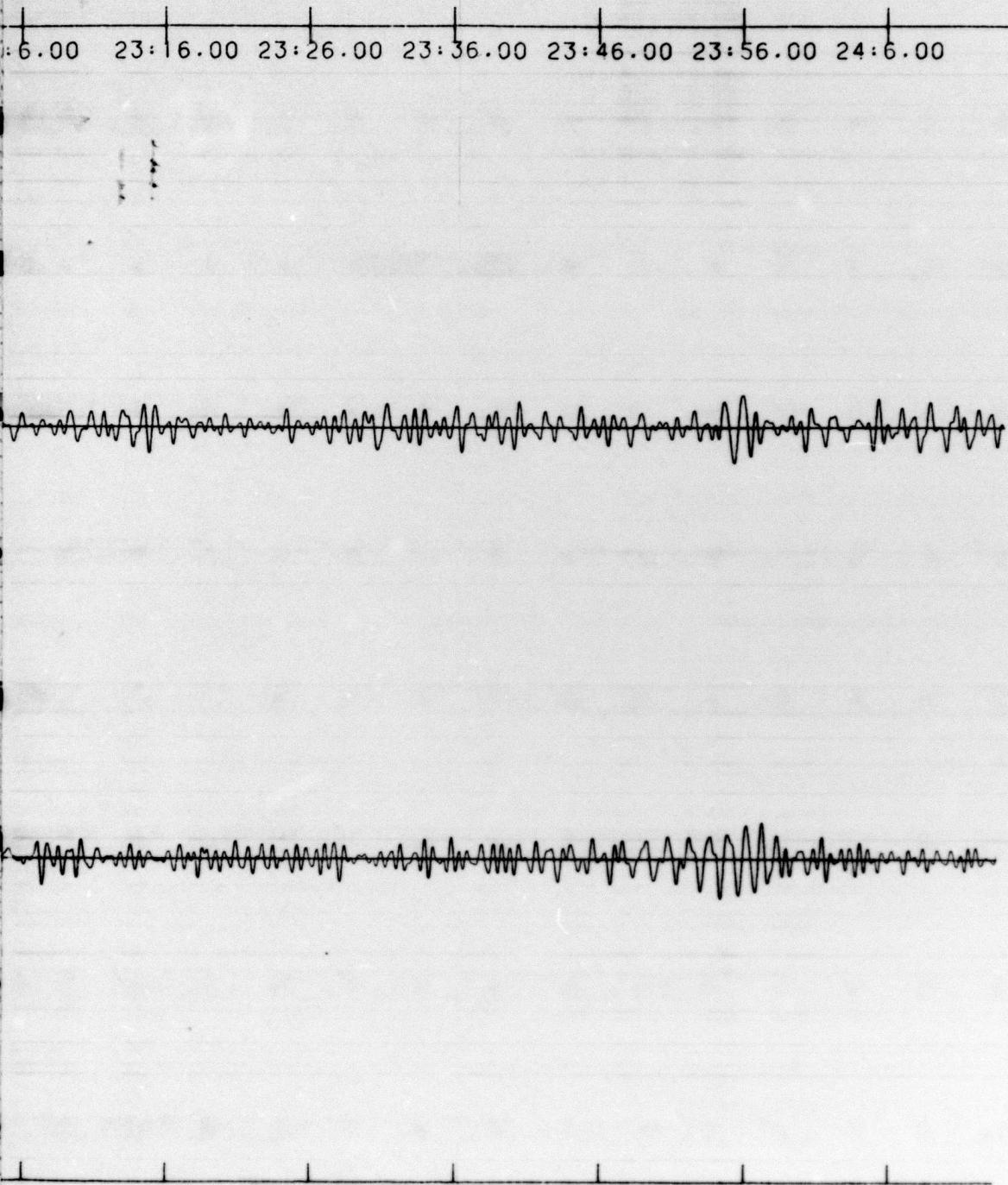


FIGURE 26. STRAIN-INERTIAL RECORDING OF LOCAL
SEISMIC EVENT DATA FILTER, 0.5 - 2.0 HZ,
4 POLE

G14658

6-19/20

TR 83-9

7. STRAIN-INERTIAL SYSTEM RECOMMENDATIONS

As indicated in the previous section on strain-inertial field tests, several modifications have been made which reduced the strain system noise level; however, to take full advantage of the system design concept, a further reduction in system noise level to a value of $2 \times 10^{-12} \text{ m}/\sqrt{\text{Hz}}$ will be required.

A review of all available data on the present noise level of the strain system has brought out the following points:

1. The strain bridge consists of four identical capacitor sections arranged in a Wheatstone bridge.
2. With the strain transducer blocked, and the bridge balanced, the output of the bridge should be zero for all frequencies.
3. The bridge actually produces a small harmonic output when set for zero output at the fundamental carrier frequency.
4. The bridge also produces a low level of white noise, which would not be expected from pure capacitors.
5. The present system noise level results from the deviation of the four capacitor sections from pure capacitors.
6. These imperfections undoubtedly result from the properties of the dielectric fluid between the capacitor plates.

We think that further reduction in the instrument noise level of the strain system will require that the strain bridge be enclosed in a vacuum so as to eliminate the dielectric problem.

An engineering study has been undertaken to examine a number of technical aspects involved in designing a strain bridge within a hard-vacuum environment, including the following:

1. Entry of strain motion and centering motion into the vacuum environment while excluding atmospheric noise.
2. Provision of mechanical damping for moving armatures within the vacuum environment.
3. Design approach for detection bridge which will allow final adjustment prior to vacuum sealing.

This study has resulted in a feasible design concept which can be implemented with minor changes in the existing strain-inertial seismometer, and we recommend this course of action.